Heterodyne Array Technology for SOFIA

SOFIA Tele-Talk

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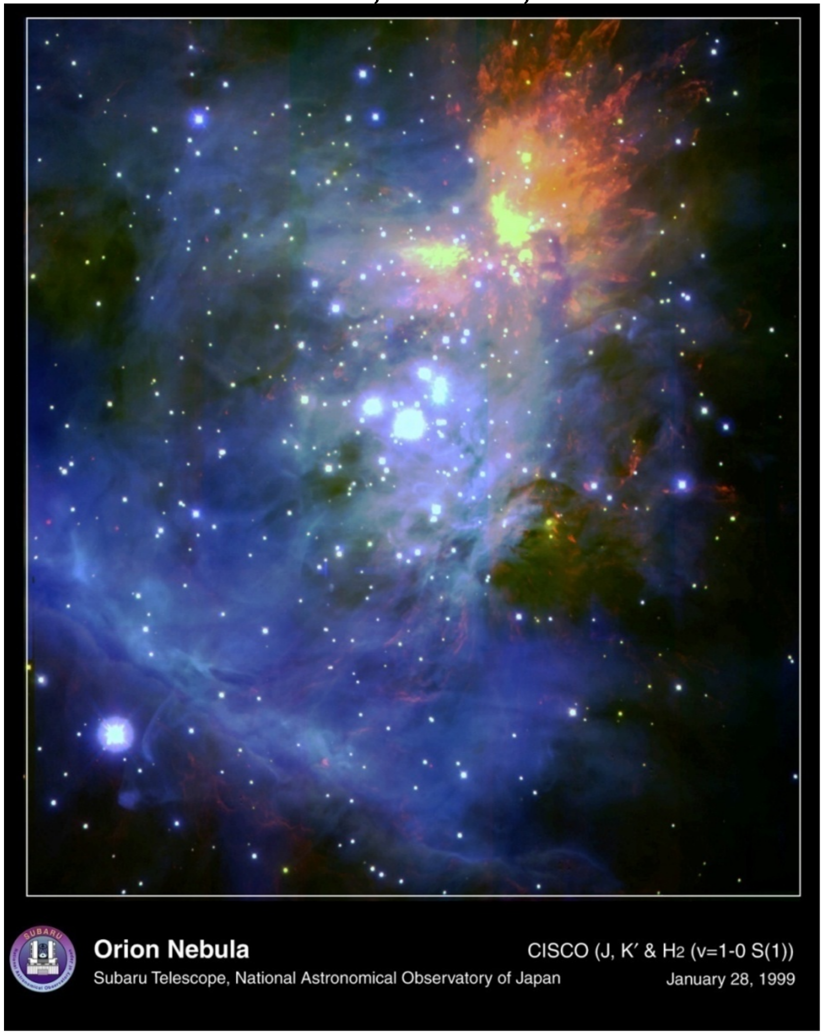
Outline

- **Objectives and Goals**
  - Objectives and goals of investigation
  - Submillimeter Tracers of High-Mass Star Formation
  - Water and Solar System Astronomy
- **Technical Activities**
  - HEB Mixers
  - Accomplishments and milestones achieved, findings, results
  - Work remaining and upcoming milestones and their success criteria
- **Final Thoughts**

Objectives and Goals

Submillimeter Tracers of Complex High-Mass Star Forming Regions

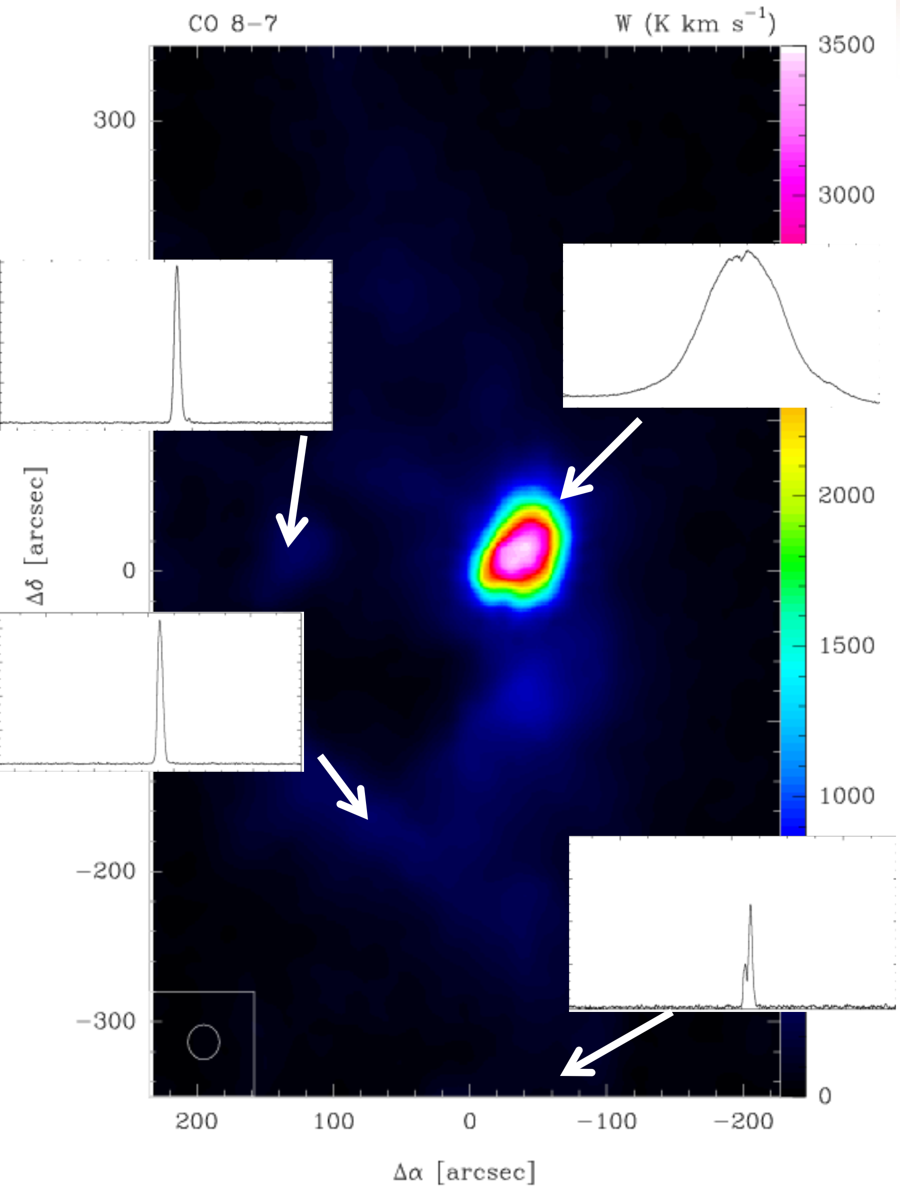
Line Diagnostics Probe Different Physical Processes including UV Irradiation, Shocks, Outflows…

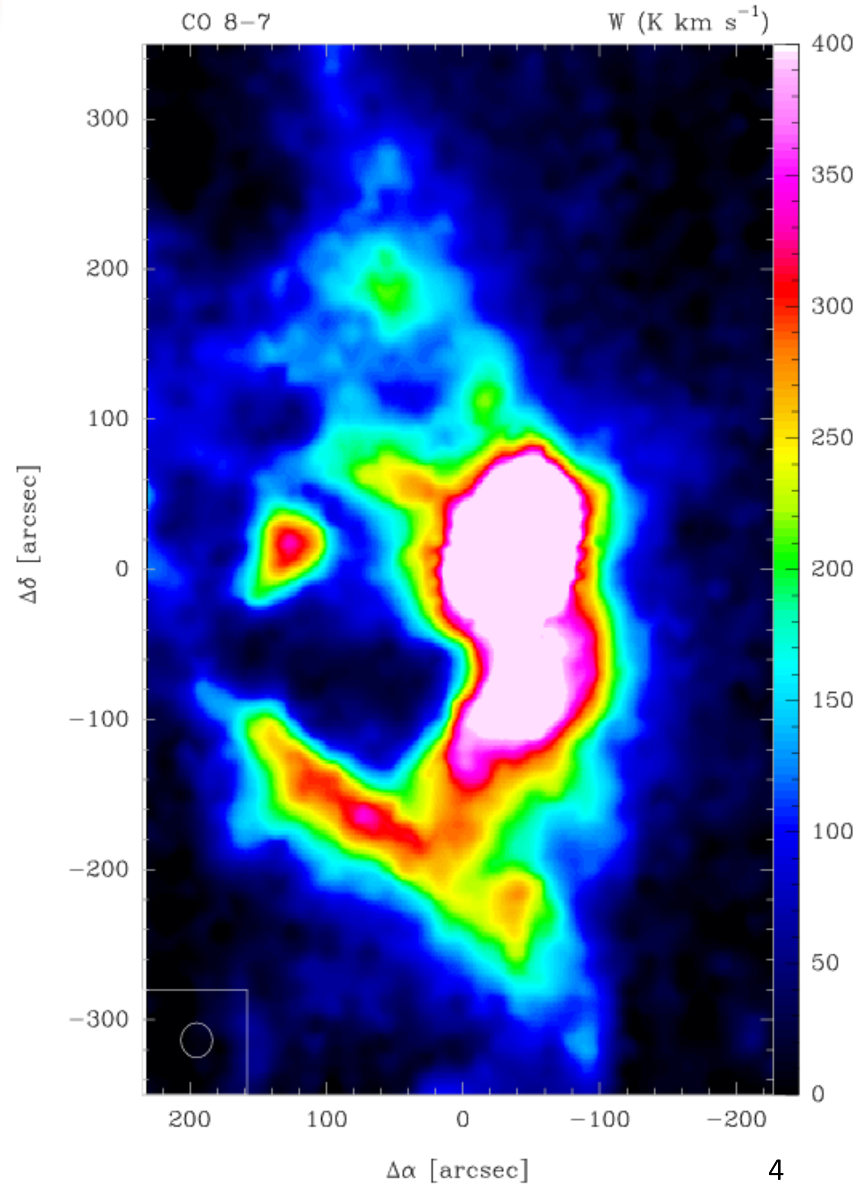


CO 8-7 @ 921 GHz
2.5 hr, beam=24"

ORION

OT1 Goicoechea et al.
7.5' x 11.5' Maps of Orion

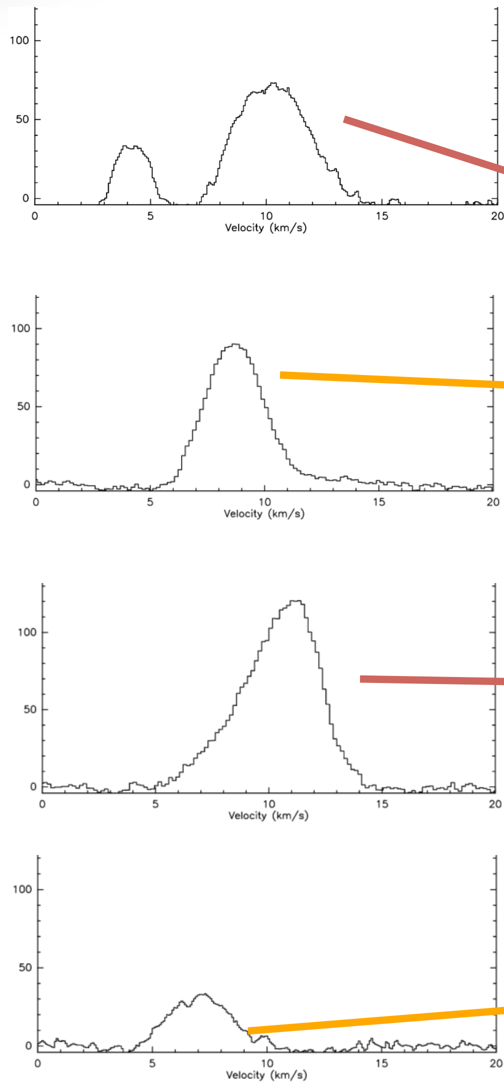


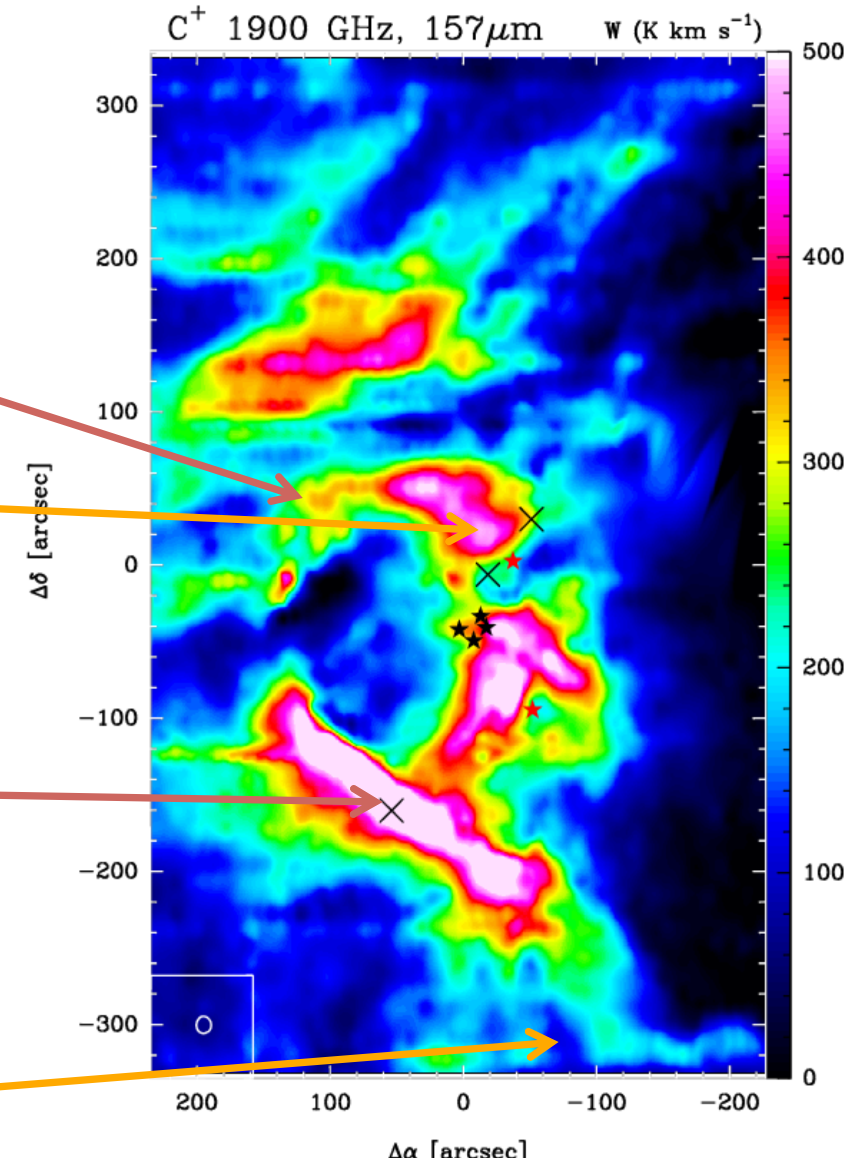


UV-irradiated neutral gas
Complex kinematics → line profiles.

C^+ @ 1900 GHz
9 hr, beam=11.6”

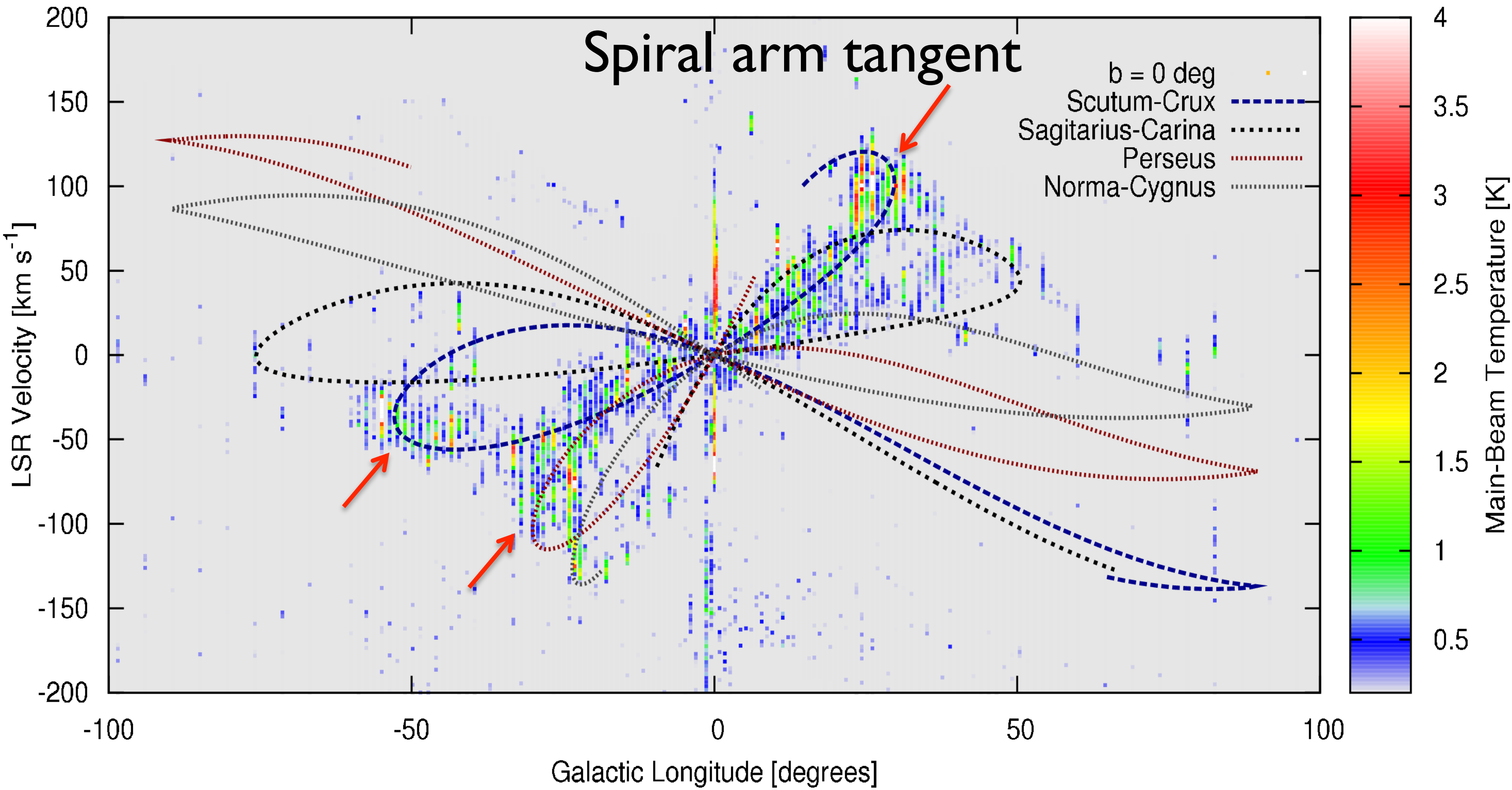
5.3 hr, beam=26’’





OT1 Goicoechea et al.

Herschel HIFI Instrument Opened a New Era in Using C+ To Trace the ISM – **High velocity resolution allows kinematic location of emission features**



GOT C+ [CII] Distribution in the Milky Way Herschel OTKP

Galactic distribution of [CII] presented by Pineda et al. (2013) A&A 554, A103

C+ as Tracer of Molecular Cloud Structure & Evolution

"Typical" Galactic Molecular Cloud & Surroundings

Transition Zone

$0.3 < A_V < 1$ mag

H is molec. H_2

C is ionized C^+

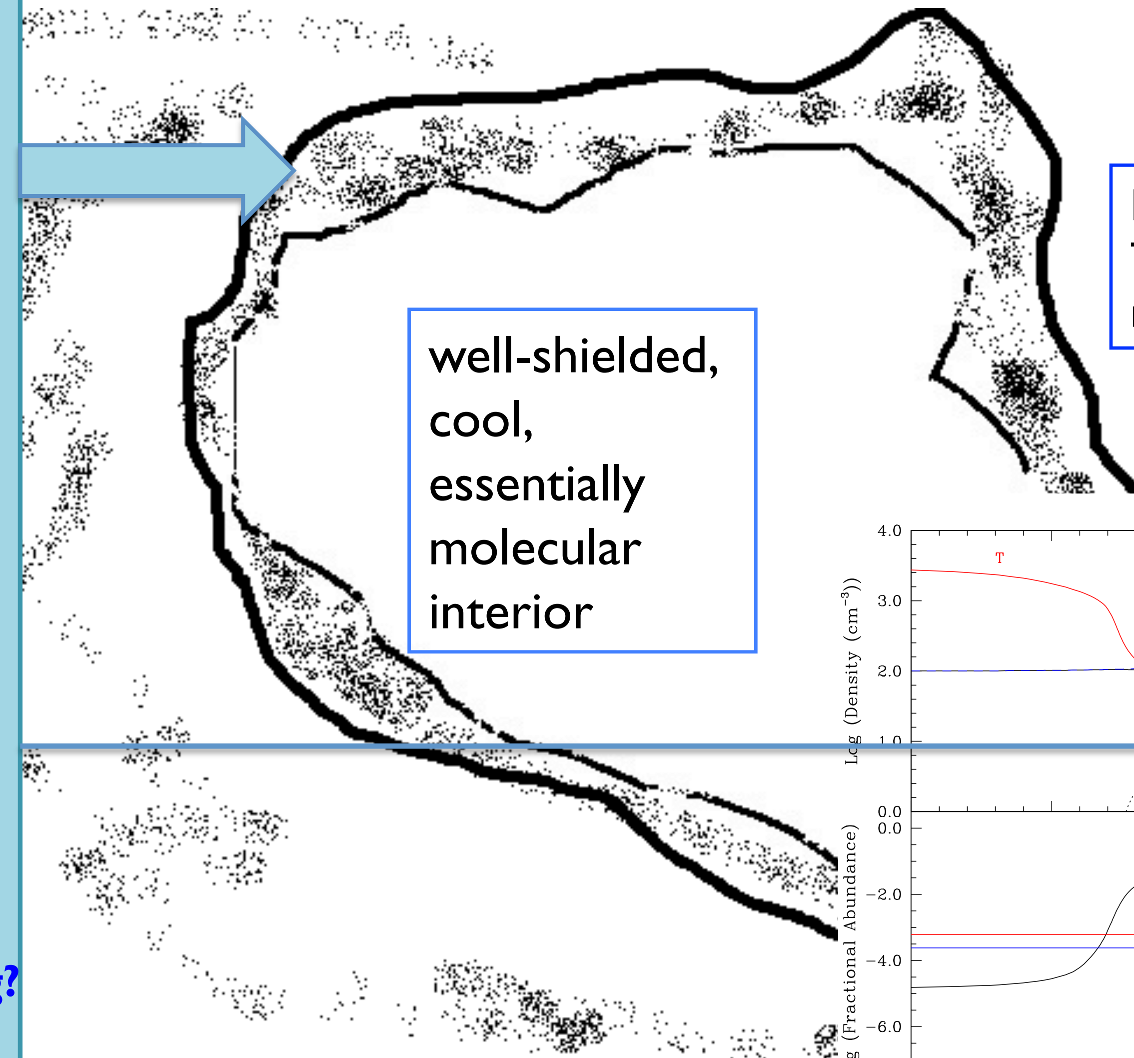
O is neutral O

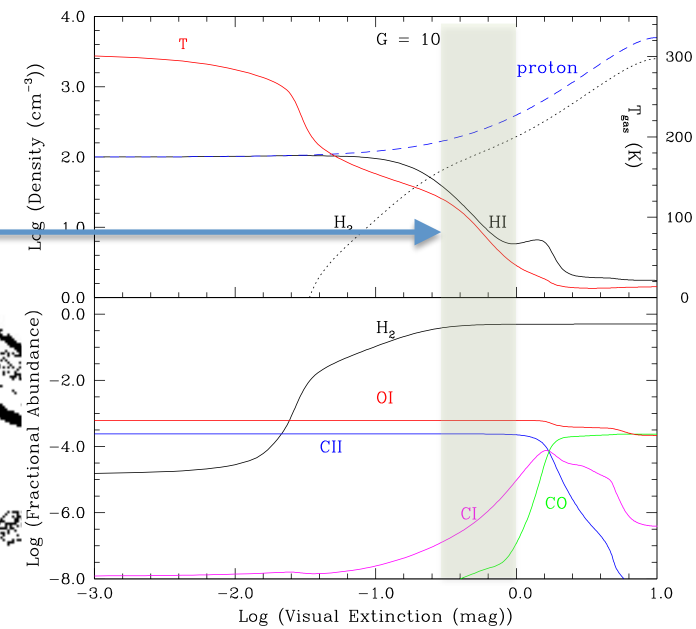
$30 < T < 120$ K

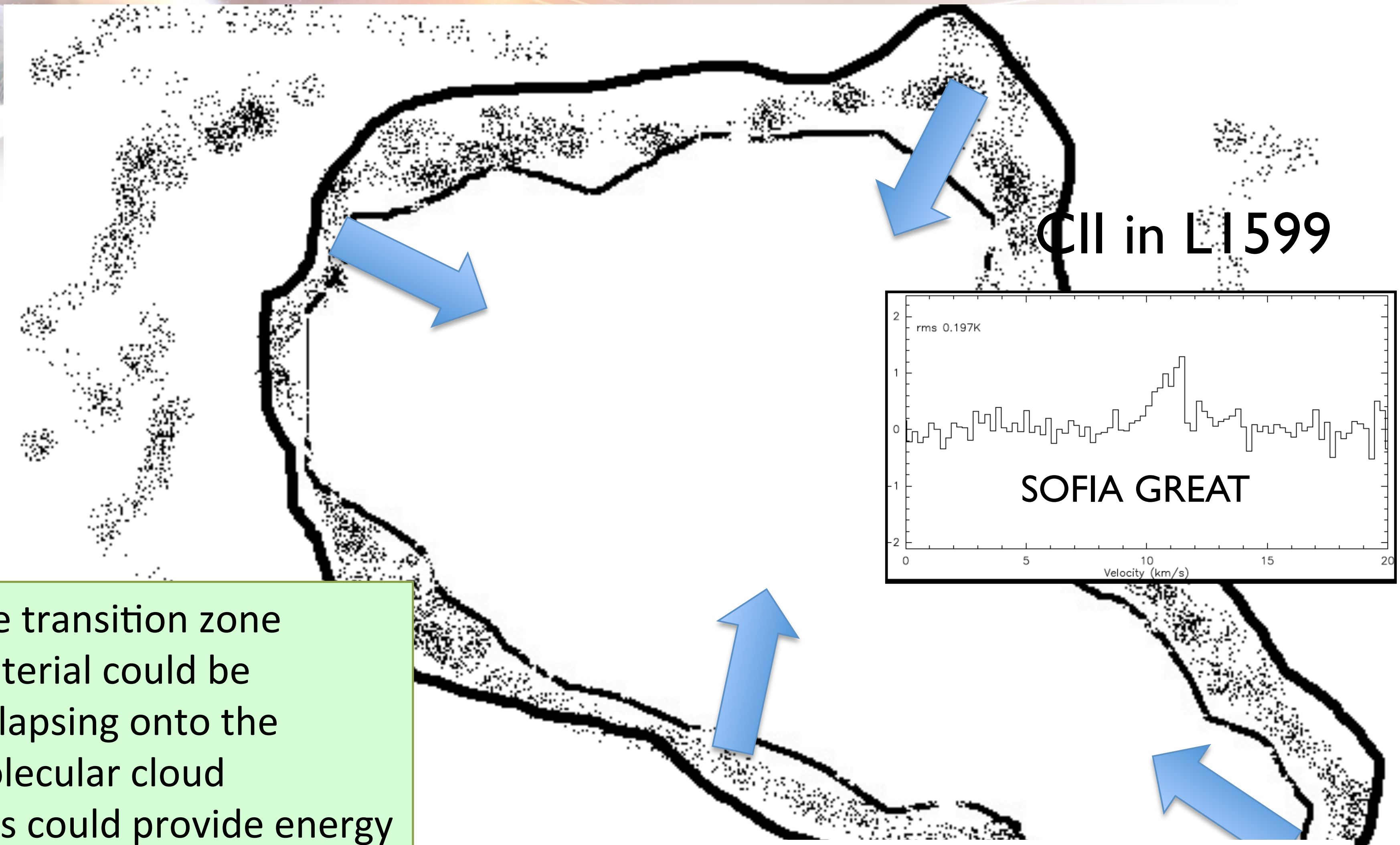
THIS IMPORTANT REGION IS BEST TRACED BY [CII] 158 μm LINE

"CO-Dark H_2" adds ~30% to mass of molecular ISM (Pineda et al. 2013)

What is this material doing?







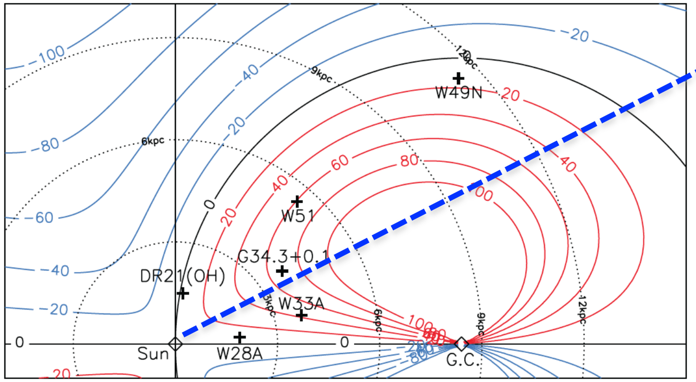
The transition zone material could be collapsing onto the molecular cloud

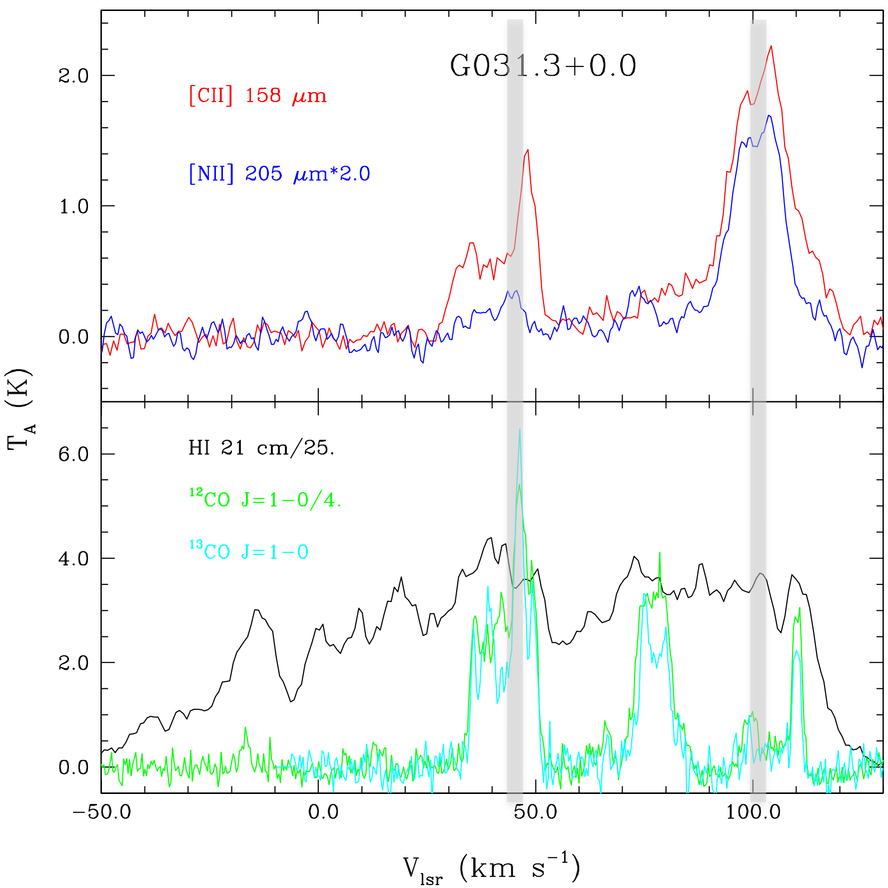
This could provide energy to sustain turbulence (Goldbaum et al. 2011)

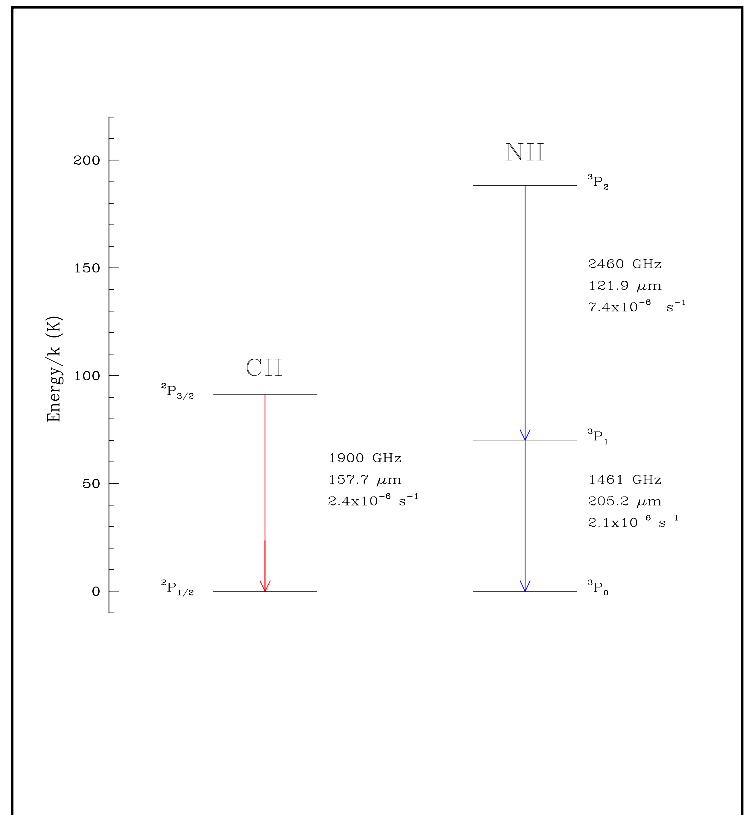
The turbulence slows and regulates star formation

We need to be able to obtain high spectral resolution (velocity-resolved) images of entire clouds to understand key physics and their evolution

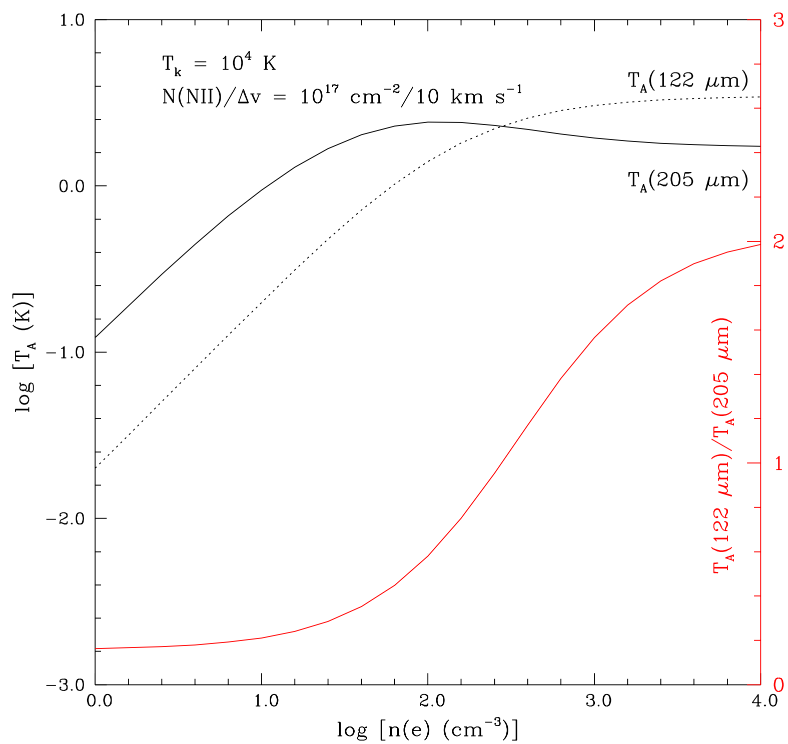
The Phases of the ISM and Star Formation

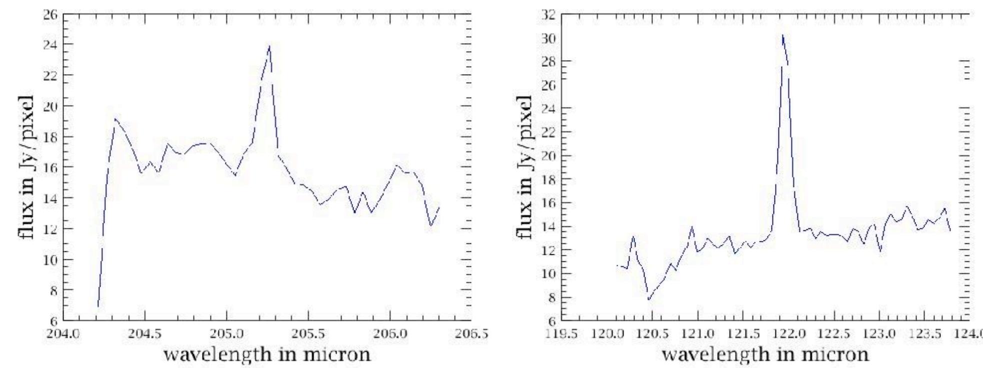


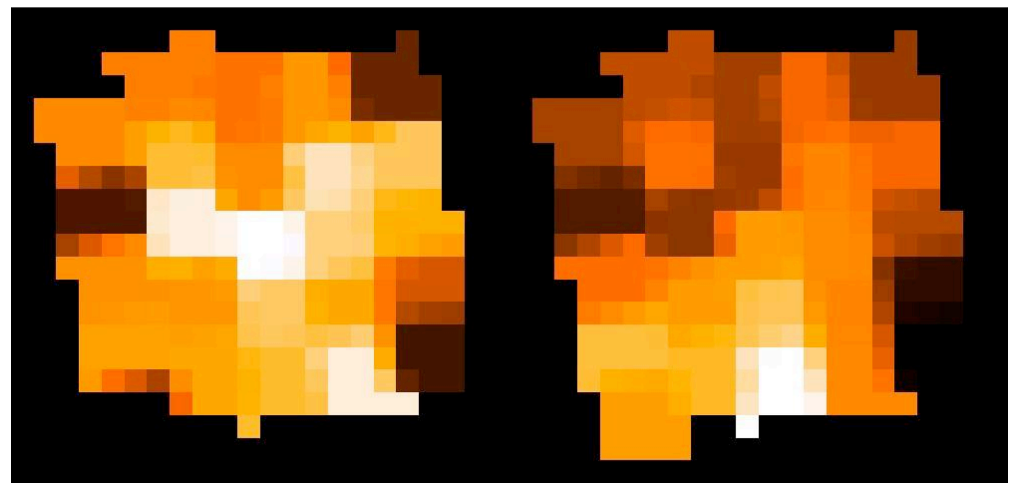




Herschel PACS [NII] Detection in G026.1+0.0

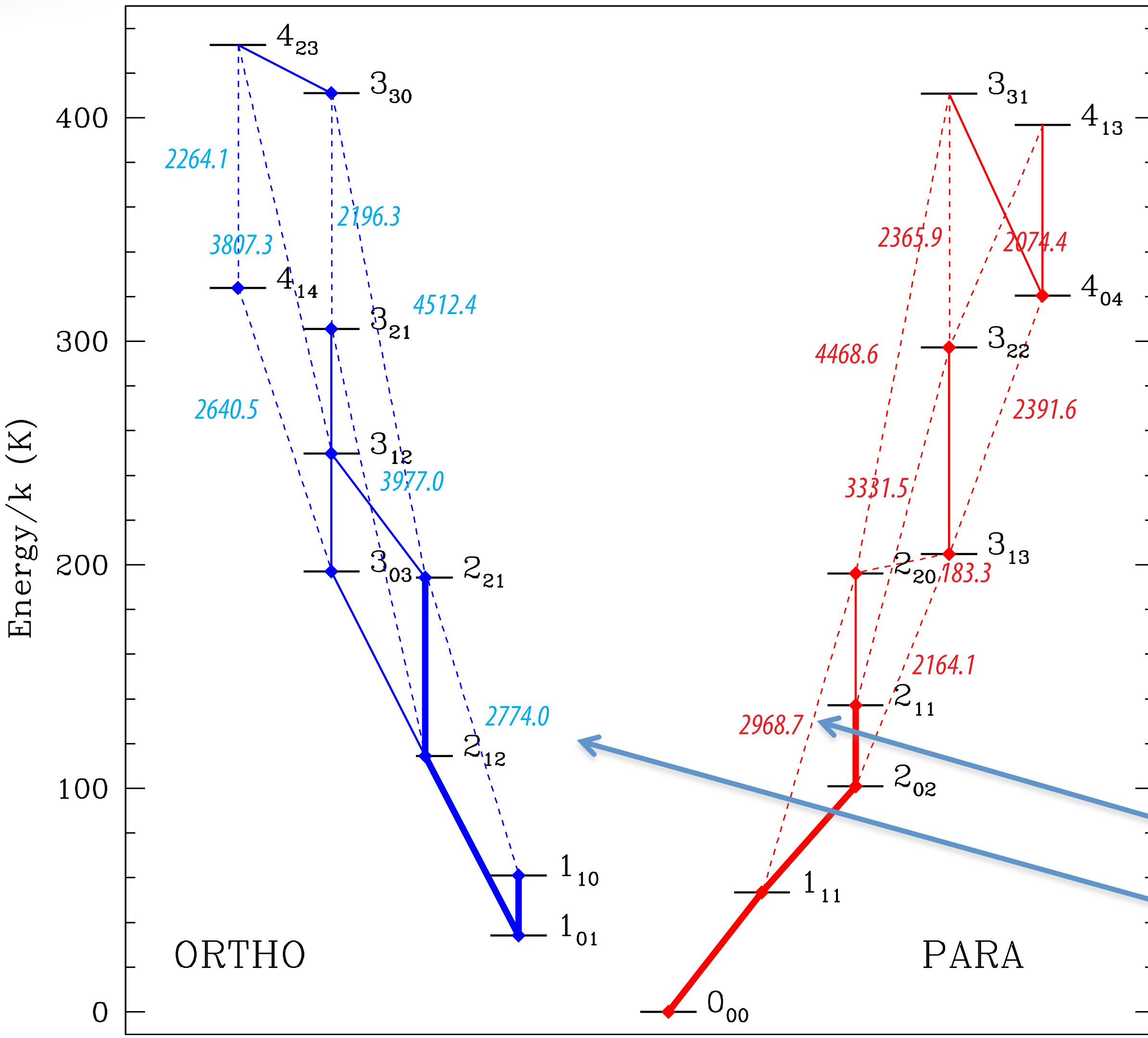






Relative Intensity of Two [NII] Lines Yields n(e)

Water is a Key Molecule in Terms of Cooling Dense Gas in Cloud Collapse and Protostar Formation

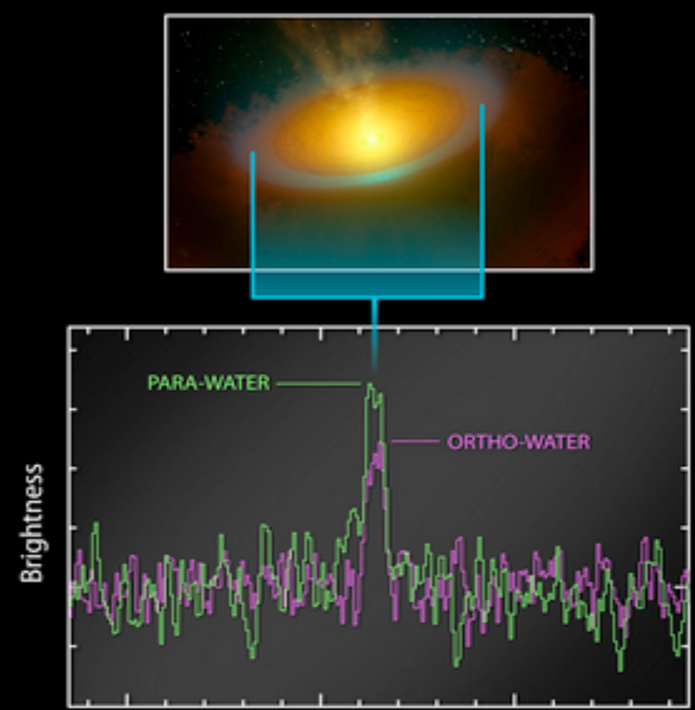


Herschel HIFI instrument observed many water lines but only up to ~ 2 THz

Two low-lying transitions are prime targets for higher-frequency instrument

1_{11}–2_{20} 2969 GHz

Herschel HIFI Observations of Water in Protoplanetary Disk



HIFI Spectroscopic Signatures of Water Vapor in TW Hydrae Disk
ESA/NASA/JPL-Caltech/M. Hogerheijde (Leiden Observatory)

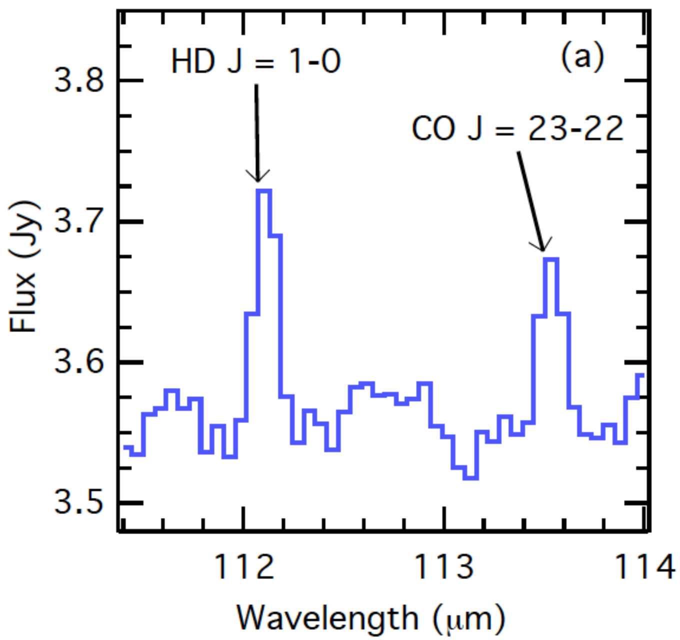
Transitions of ortho- and para-H_2O detected in disk of TW Hydrae (D = 54 pc)

Modestly young star (5 – 10 Myrs)

Water in disk could fill several thousand Earth oceans (ESA Web Release)

Water likely frozen on dust grains as is the case in interstellar clouds and liberated due to heating from the star

Detection of HD in Protoplanetary Disk Around TW Hydrae



Observations carried out with Herschel PACS instrument

No velocity or line width information

HD traces entire disk unlike CO or water which are frozen in midplane

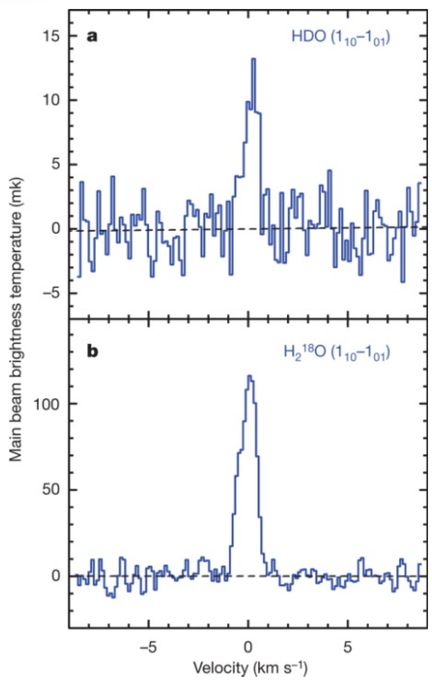
Mass of disk indicated is thus much larger than previously thought and this "old" disk may still be capable of planet formation

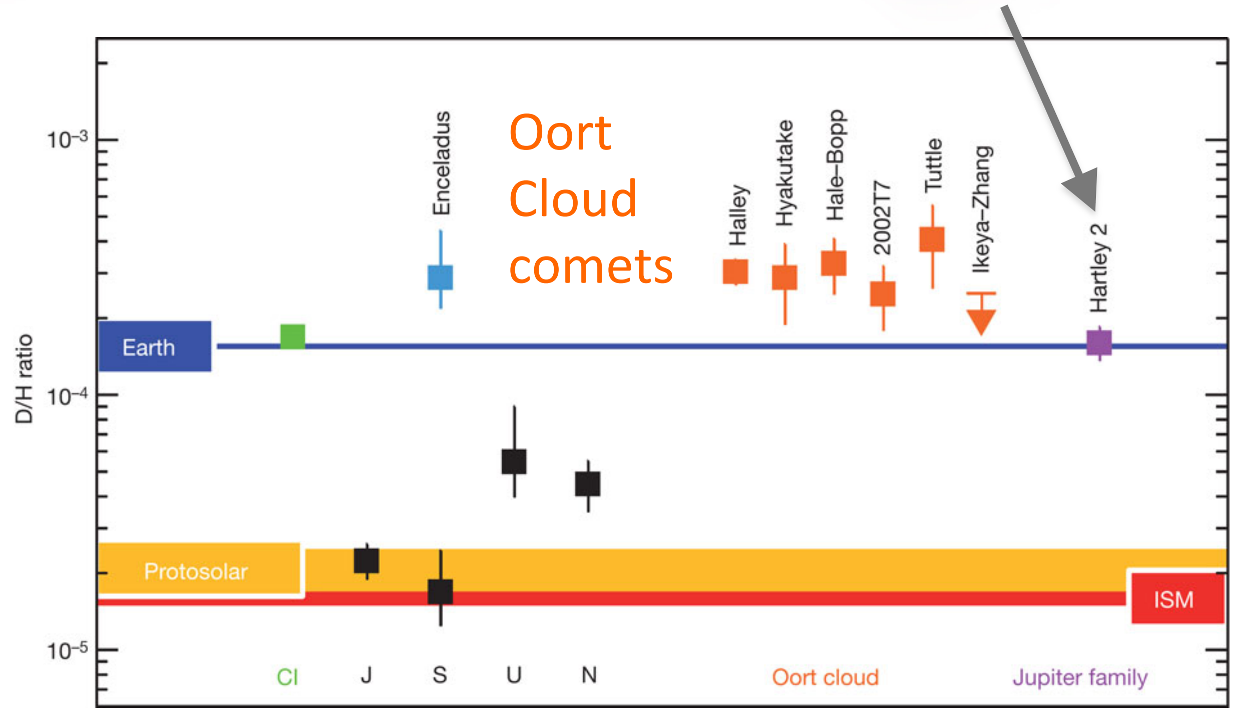
The HD J = 1–0 Line is at 2.7 THz Heterodyne receiver capable of high spectral resolution now

Water in Our Solar System

D/H Ratio in Jupiter-Family Comet 103P/Hartley2 from Herschel = $(1.61 \pm 0.24) \times 10^{-4}$

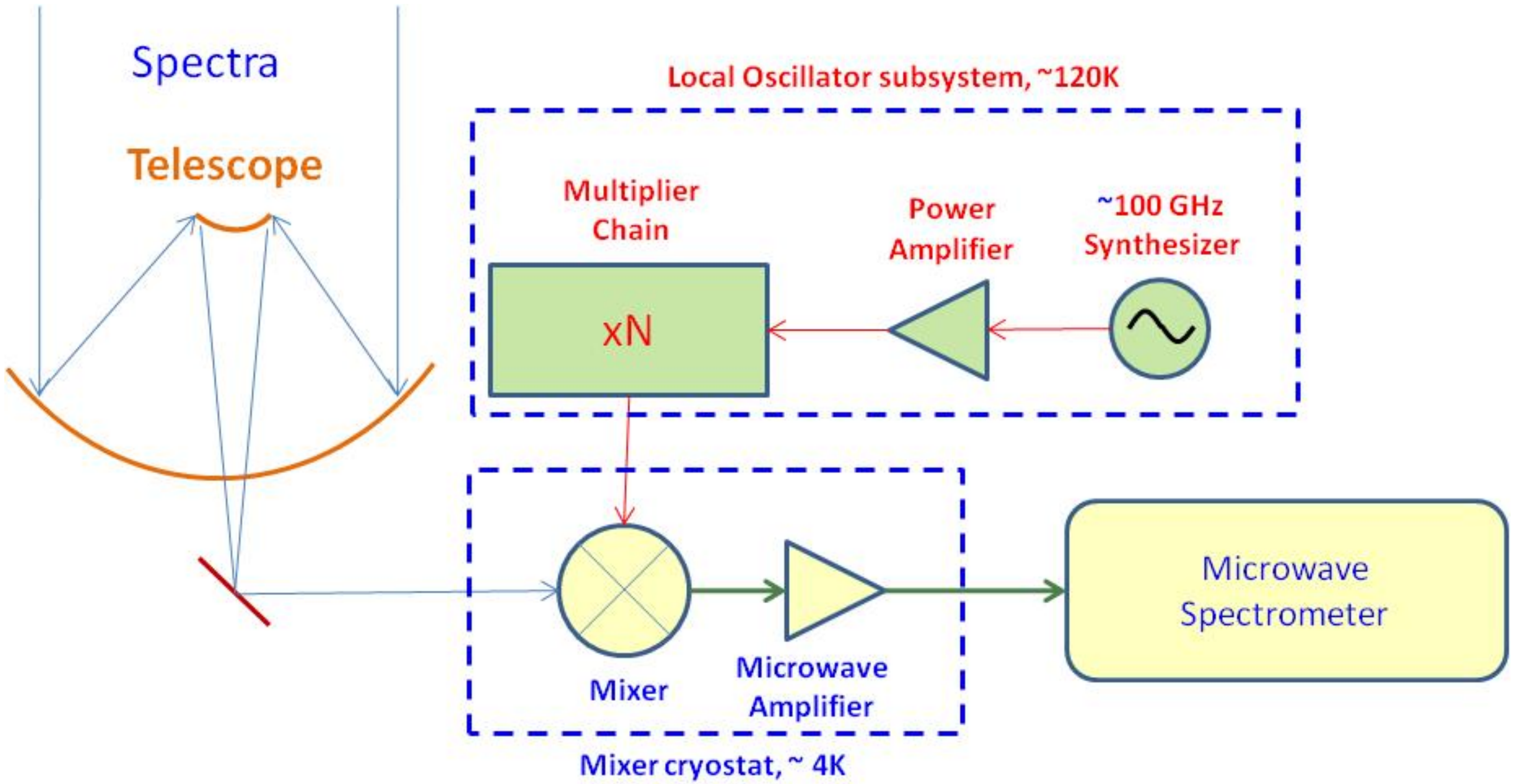
P. Hartogh, D. Lis (Caltech), D. Bocklee-Morvan et al. 2011, Nature 478, 218





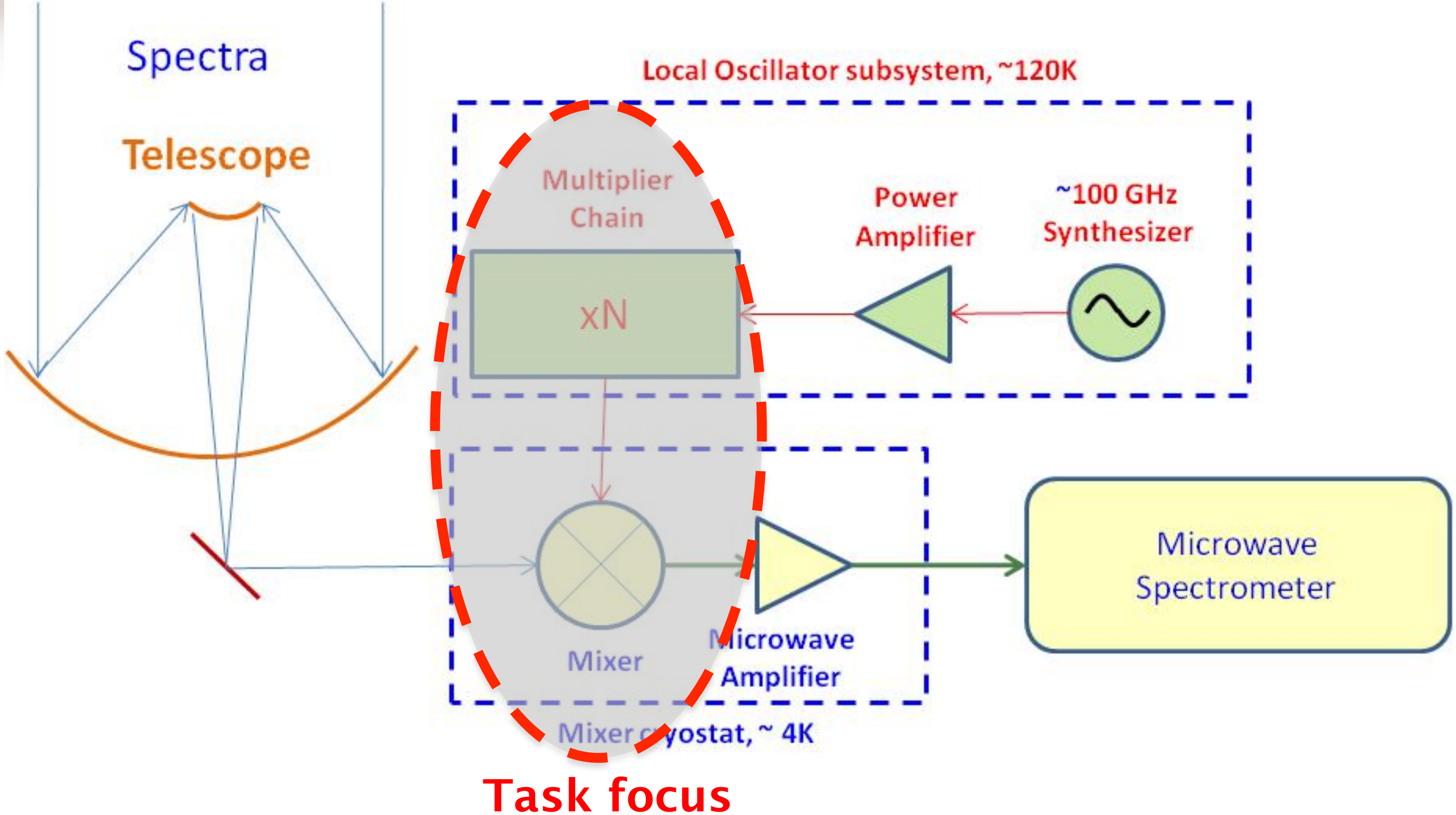
- **Agreement of D/H between Jupiter-Family comet and Earth has revived comets as reservoir for Earth's water**
- **Still many issues regarding modeling of early solar system**

Approach: Single-pixel Heterodyne Receiver for Astrophysics



Heterodyne detectors convert incoming high frequency photons to lower frequency by “mixing” them with a local oscillator signal. The down-converted signals are easy to amplify and analyze using standard microwave techniques, enabling spectral resolution as high as $\lambda/\Delta\lambda \approx 10{,}000{,}000$. The observing frequency of a heterodyne spectrometer can be modified by changing the frequency of the local oscillator.

Single-pixel Heterodyne Receiver



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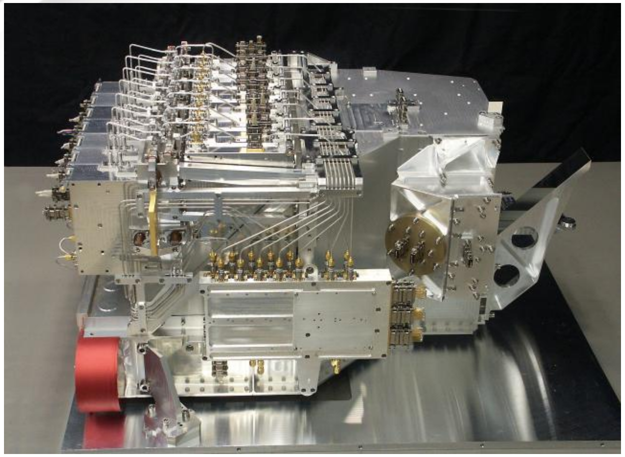
TRL Assessment

Component	Current TRL	Rationale	Comments
4-pixel Mixer	4	Mixer block demonstrated with 4 HEB devices packaged similalr to single pixel mixer blocks	
Ka-band synthesizer	4	Demonstrated in lab	
Ka-band power amp	4	Demonstrated in lab	
1st stage multiplier	4	Demonstrated in lab	
2nd stage multiplier	4	Demonstrated in lab	
3rd stage multiplier	4	Demonstrated in lab	
4th stage multiplier	4	Demonstrated in lab	
4-pixel LO	4	Demonstrated in lab	
4-pixel Receiver	3	Proof of concept validated, need to demonstrate in laboratory enviornment	Goal is to reach TRL 4

Key Challenges: Next-generation Heterodyne Instrument Development Path



SOA: HIFI focal plane unit

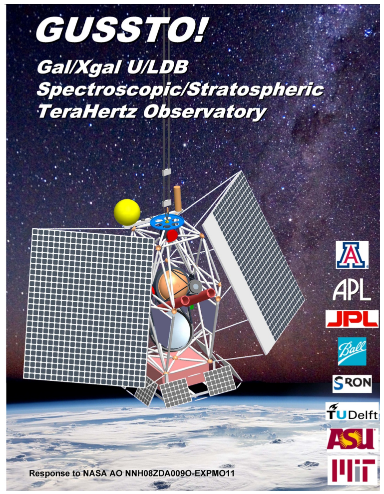
Multi-pixel THz Receiver

- Technologies for multi-pixels
- Higher power multipliers
- Higher IF bandwidths
- Efficient LO injection scheme
- Controllable LO power per pixel
- Stable subsystem
- Higher sensitivity

FUTURE MISSIONS FOR THIS TECHNOLOGY

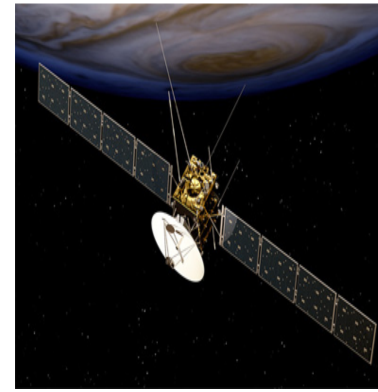
SOFIA Airborne MISSIONS

GUSSTO Balloon



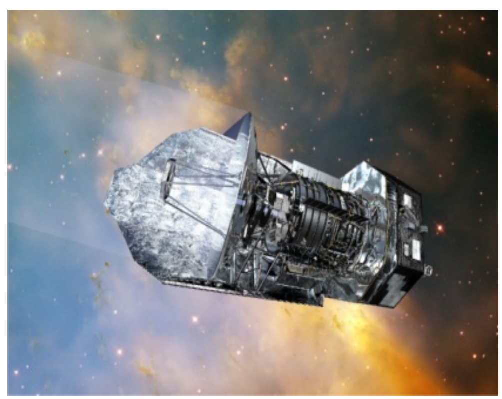
CIDRE

JUPITER

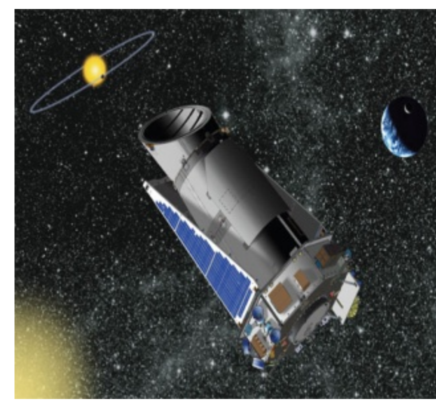


CCAT

Millimetron



HIFI (follow on)



Objectives and Goals—Technology Development

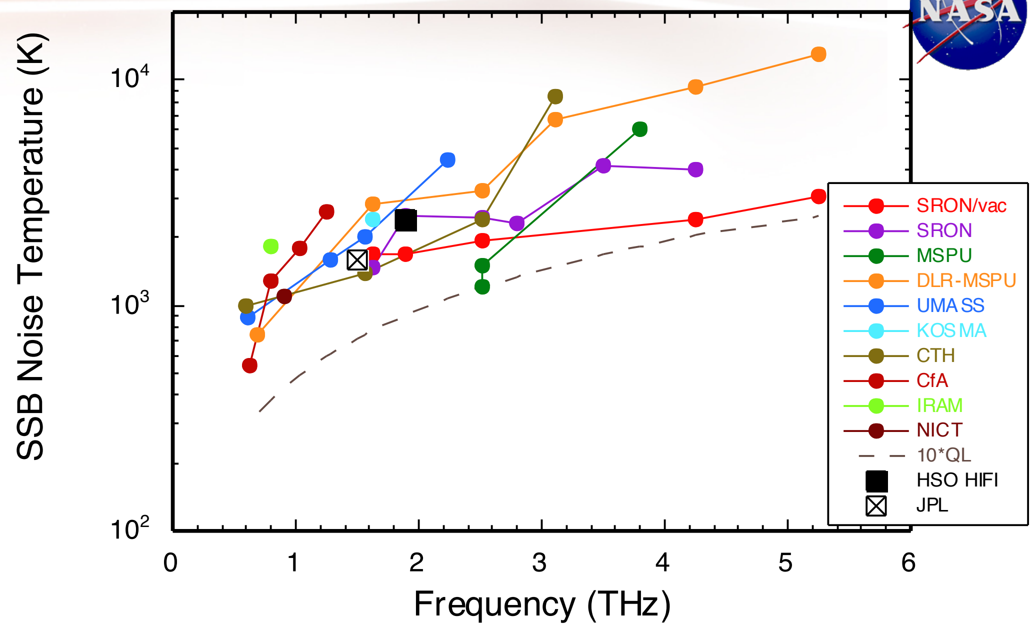
- **While HIFI has been successful, heterodyne systems at frequencies above 1.5 THz are still in their infancy, and dramatic improvements can be anticipated if technology program is available to support this**
- **High spectral resolution observations are not significantly affected by background, and thus have great potential for platforms like SOFIA**
- **The key objectives are to**
  - (1) improve pixel sensitivity;
  - (2) develop arrays to enable submillimeter heterodyne cameras;
  - (3) increase bandwidth of the 1.9 THz LO subsystem, and
  - (4) extend frequency range to cover up to 5 THz frequency

HEB Technology

T_r(SSB) at 1.9 THz

HIFI : T_r = 2400 K
And $Df_{IF} \leq 4$ GHz

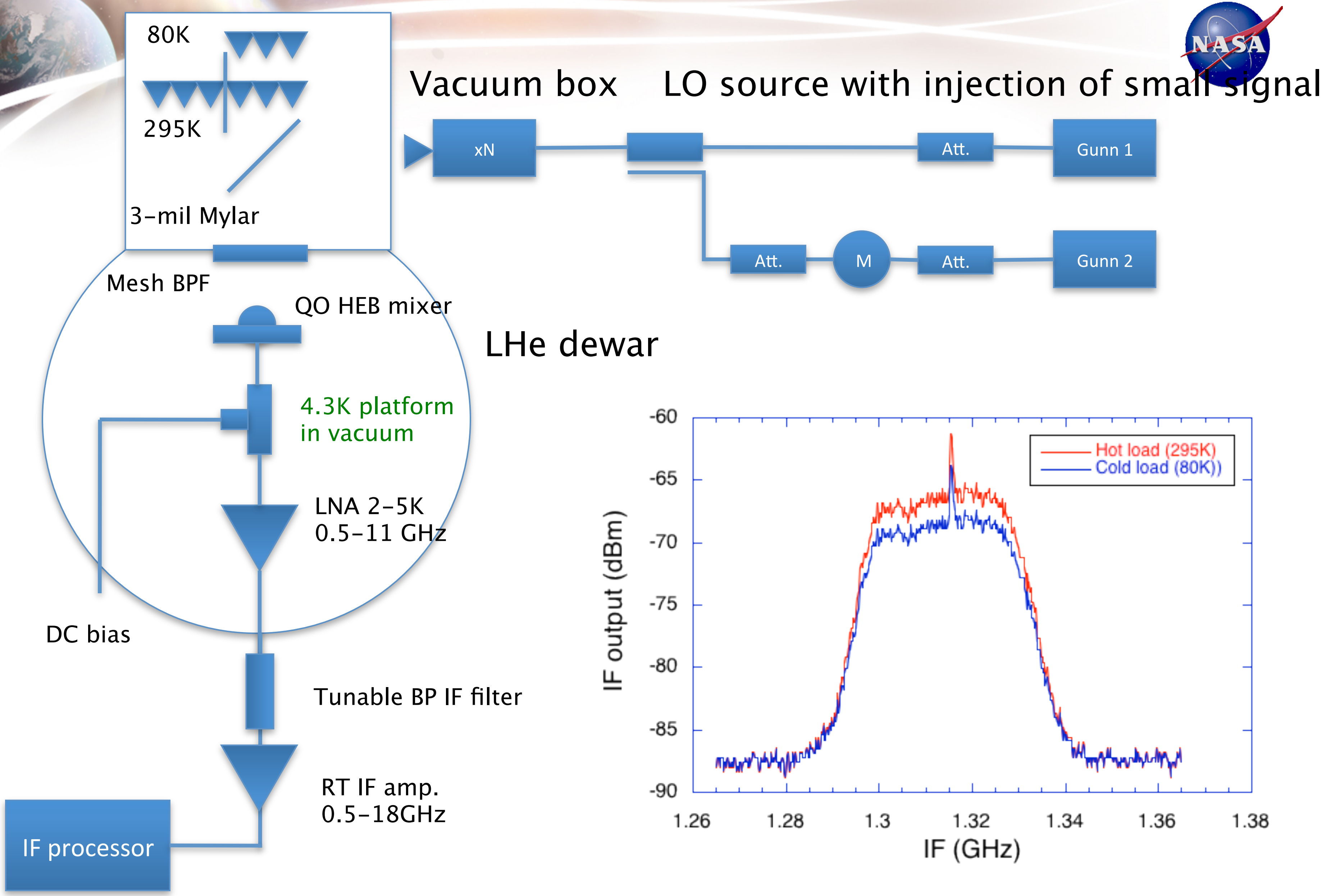
Goal: T_r = 1000 K,
And $Df_{IF} \leq 8$ GHz



The Approach:

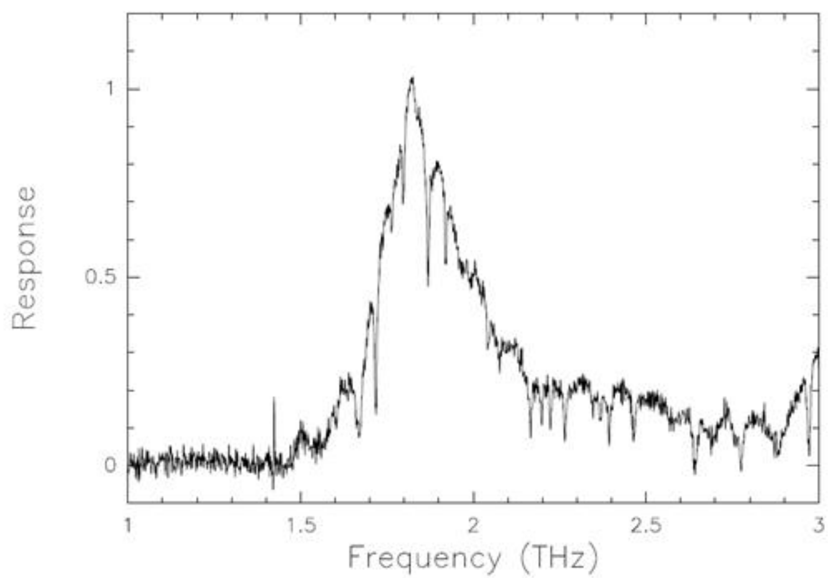
- Design planar antenna-coupled quasioptical devices which are currently standard in the research community;
- Use a dedicated test bench incorporating best practices in the HEB mixer tests (reduced optical bandwidth to eliminate the direct detection effect; injection of an additional monochromatic signal to control the correlation between the noise temperature and the conversion efficiency; vacuum test chamber to eliminate atmospheric loss and related instabilities);
- Characterize devices made by MSPU lab (Moscow, Russia);
- Implement fab process with *in-situ* gold contacts which allows for the largest Df_{IF} and lowest T_N in the recent MSPU devices.

Setup for characterization of HEB mixers



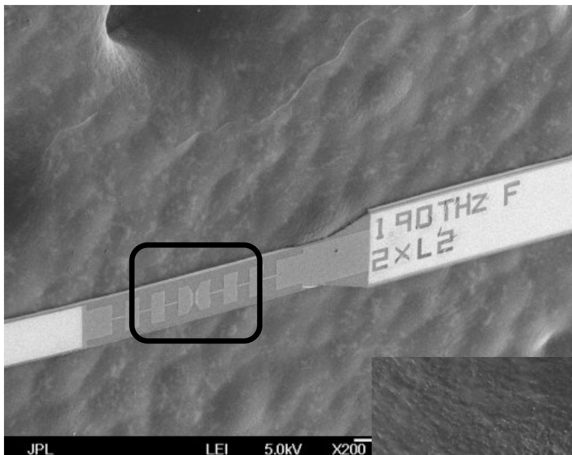
JPL 1.9 THz HEB Devices

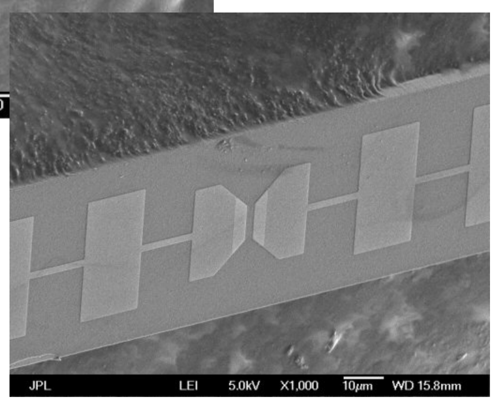
- Mixers working at 1.9 THz have been fabricated at JPL.
- FTS measurement shows that the mixer circuit design is slightly detuned from the design center frequency of 1.9 THz, the rest frequency of C^+. Electromagnetic modeling shows that this shift was caused by a thin layer of SiO2 applied to the mixer devices for purposes of passivation and protection.
- Design can be tuned be readily compensated by using mixer devices tuned for slightly higher frequency operation, e.g., 2 THz.
- The response of the mixer shows numerous absorption features caused by water vapor in the ~1 cm air path between the mixer cryostat and the window of the evacuated FTS.



Scalable 1.9 THz Mixer Technology

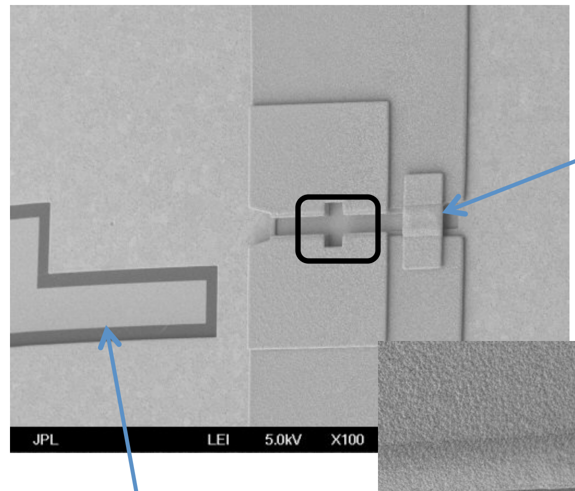
HEBs fabricated on thin Silicon On Insulator (SOI) lets us make waveguide chips that work from 500 GHz to 5 THz. Because we etch the chip, we can use a non-rectangular shape.





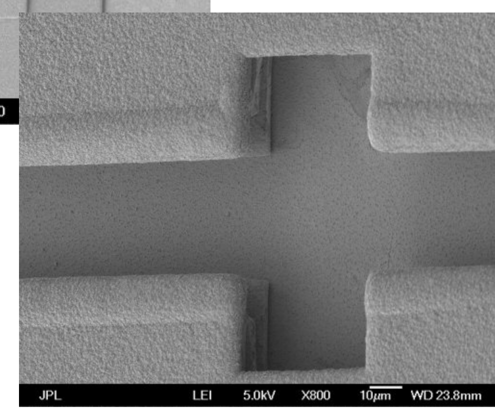
The initial run of 1.9 THz mixers has been completed. Testing should begin later this month.

Gold plated back pieces are easily mass produced and superior to conventionally machined parts using deep UV lithography. This third generation part has an integrated IF bond pad and suspended ground side bond pad.

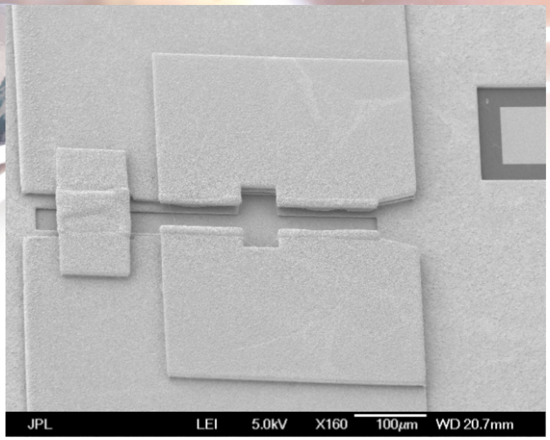


A suspended ground tab will be connected to the mixer using a wire-bond tool.

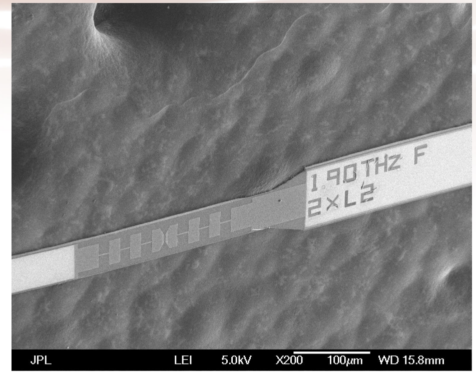
Integrated bond pads will make assembly simpler and more robust.



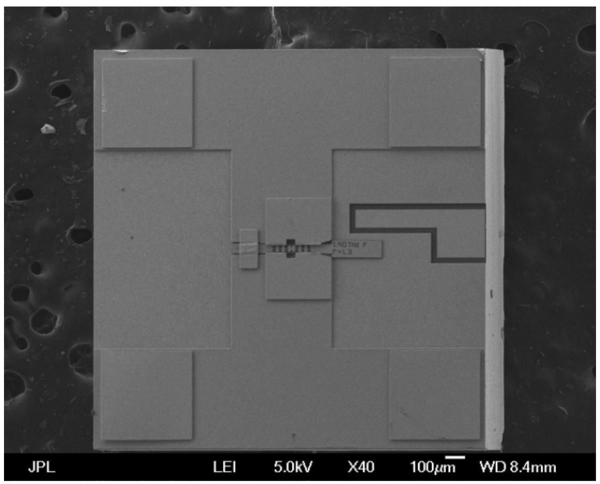
Single pixel JPL Mixer

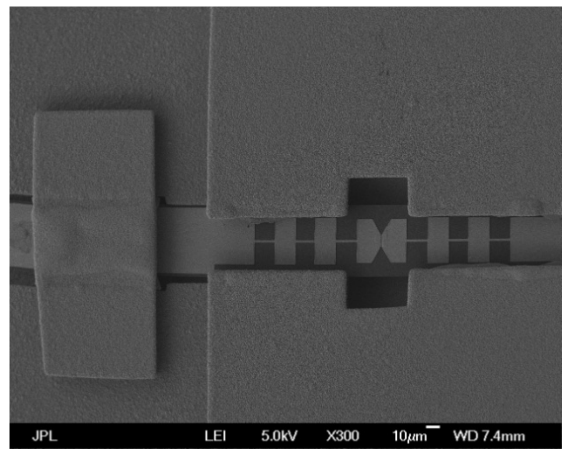


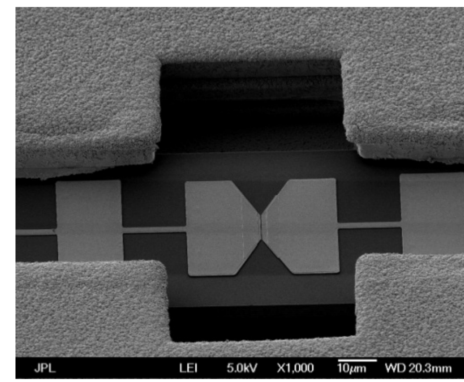
Silicon wafer with Multiple gold depositions



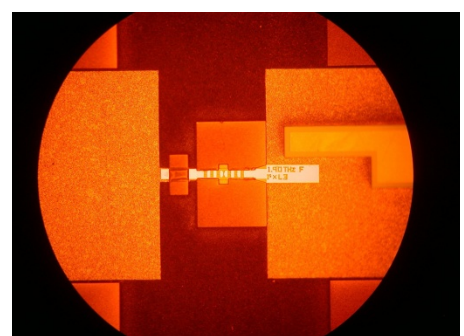
NbN HEB device on SOI





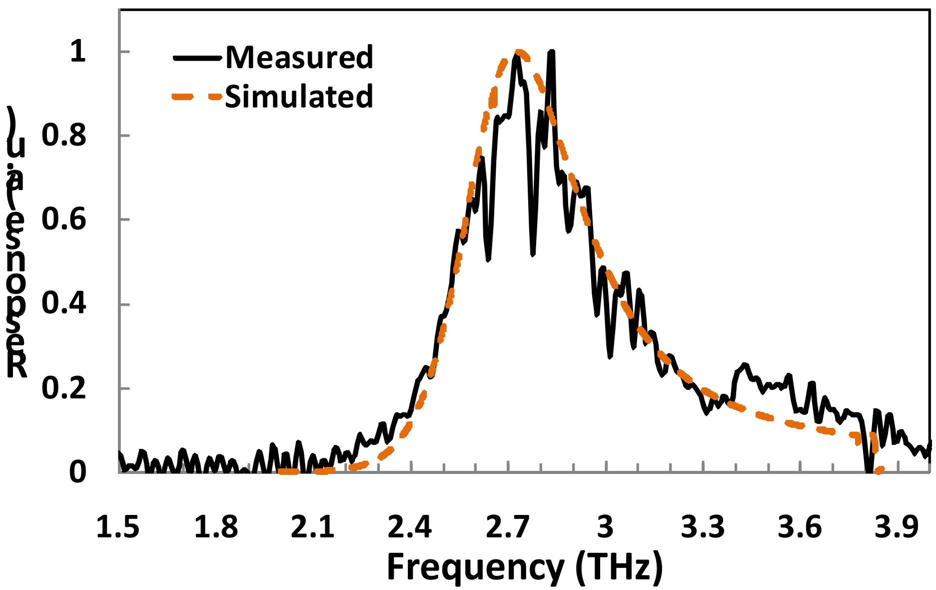


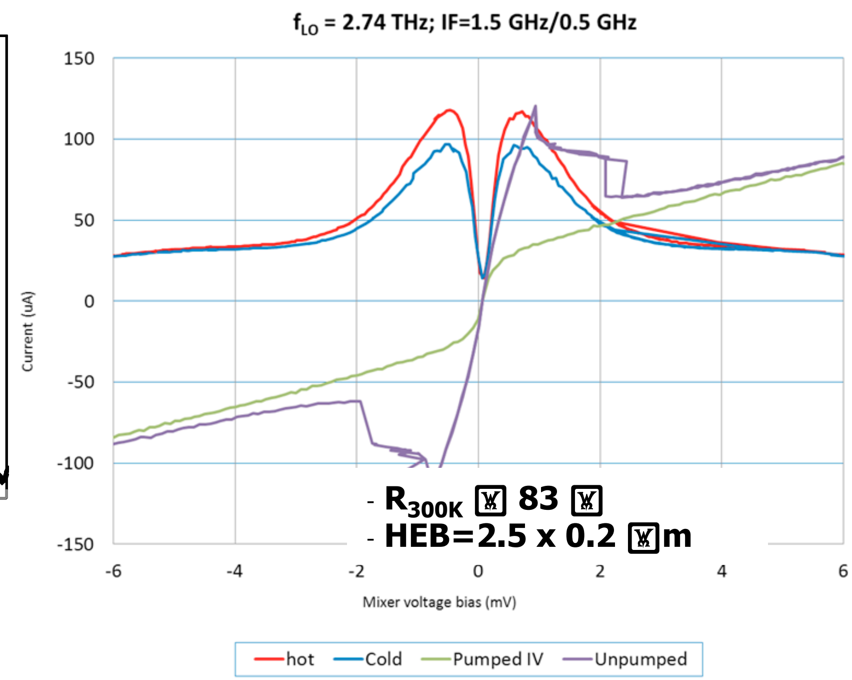
These parts are made by electro-plating of gold or copper and epoxy based KMPR-1025 resist.



Optical/SEM images of mixer device in silicon package

2.7 THz Mixer development



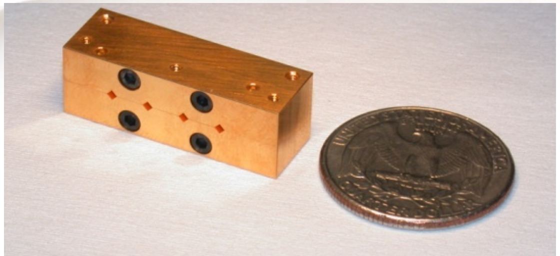


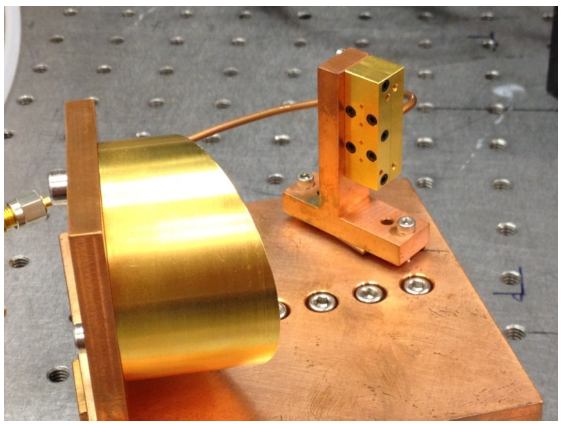
- 2.7 THz mixer response measured by Fourier-transform spectrometer (solid line). The sharp dips in the measured response near 2.65 THz and 2.8 THz are caused by absorption of *water vapor* in the short optical path between the mixer cryostat and the evacuated FTS.

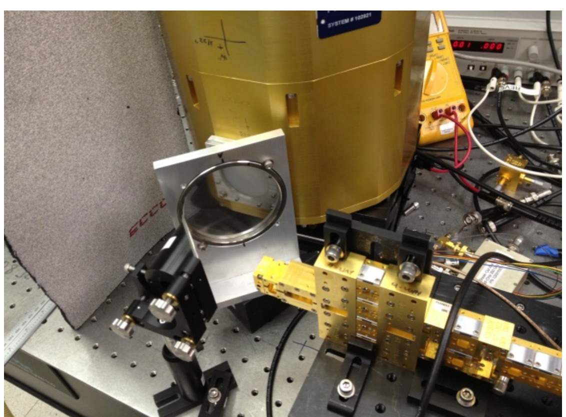
- Uncorrected DSB noise temperature: T_{rec} □ **965 K @ 2.74 THz (DSB)**

Mixer also tested with JPL solid state LO chain at 2.56 THz. Measured DSB T_{rec}= 1350 K.

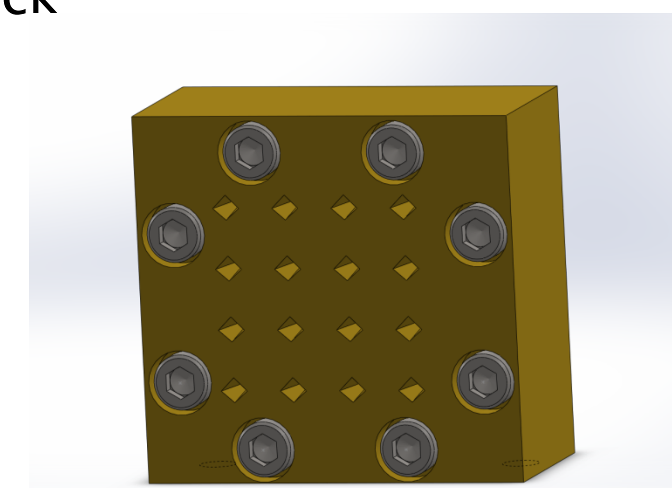
4-pixel mixer block has been fabricated



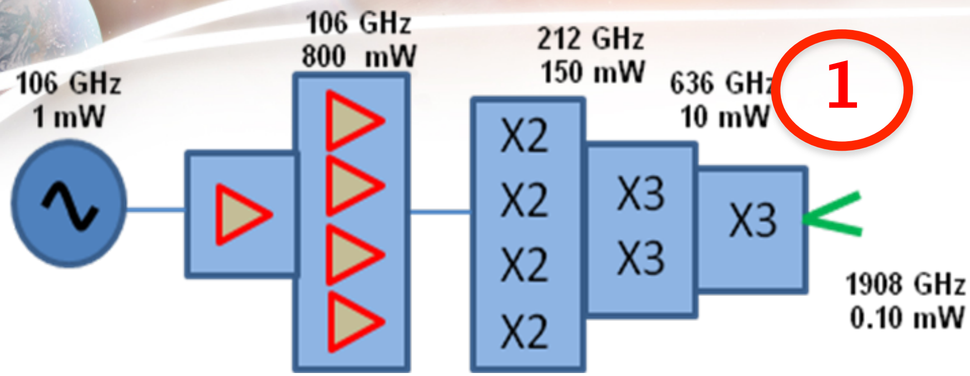


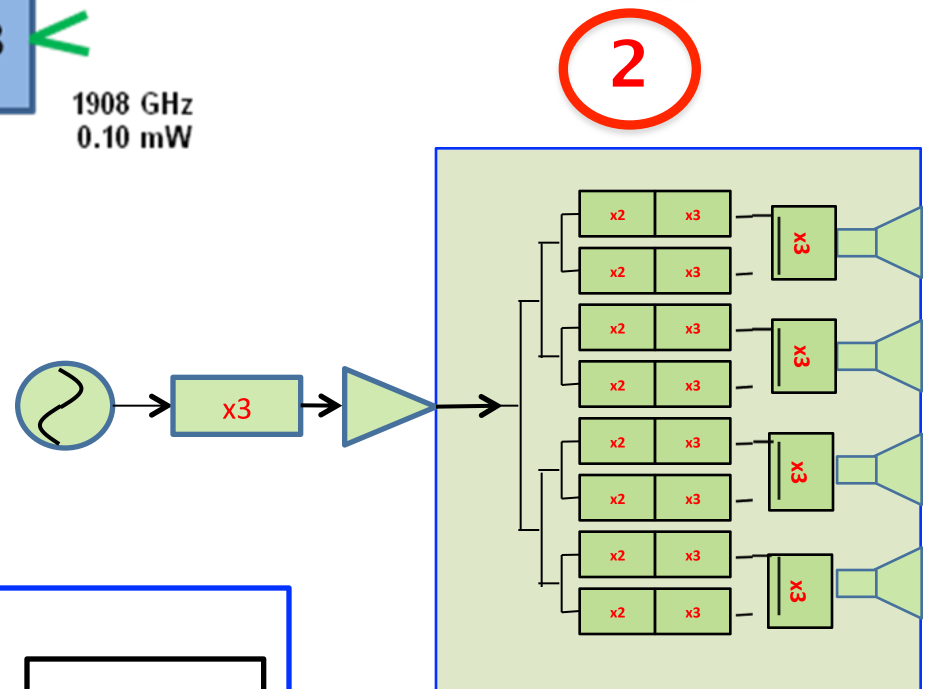


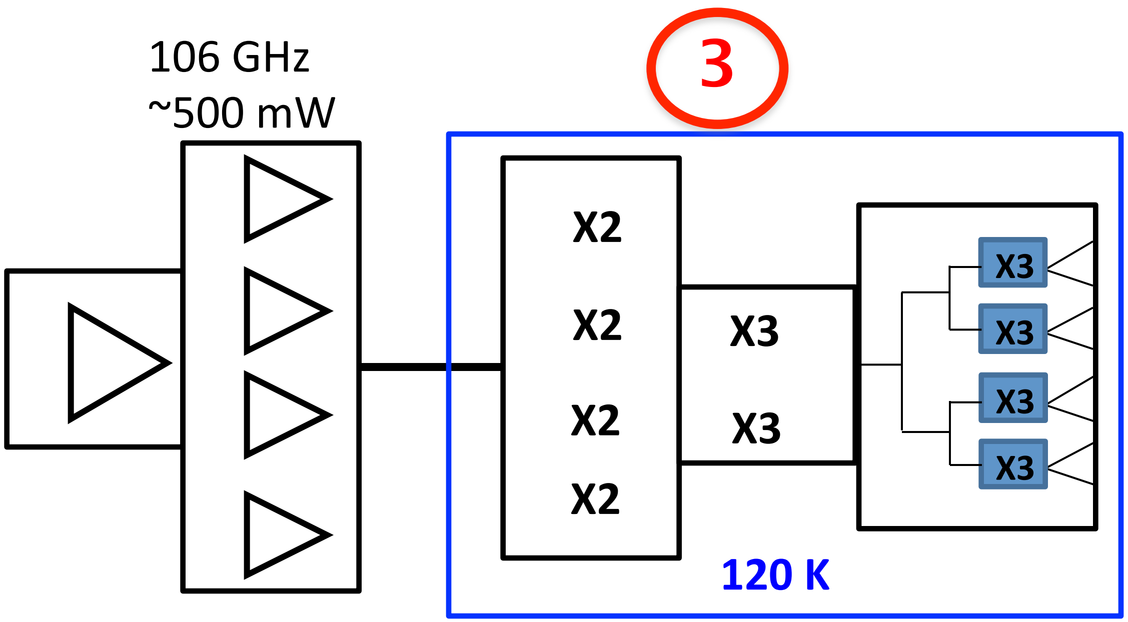
- A 4-pixel 1.9 THz mixer block has been fabricated
- The block has been inspected and accepted
- Verified receiver operation filling one pixel and using one pixel LO
- Clear path to a 16-pixel mixer block



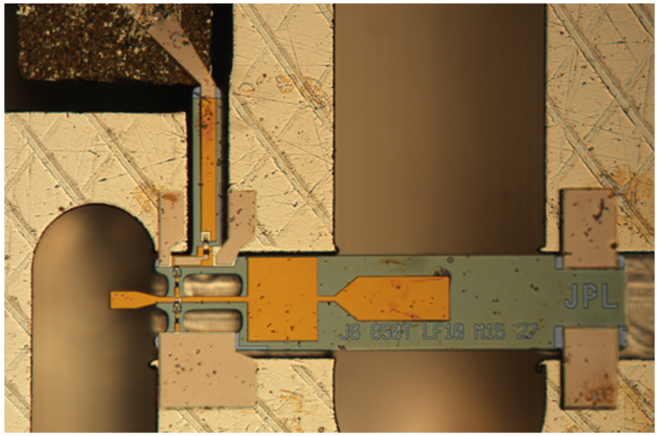
LO Architectures

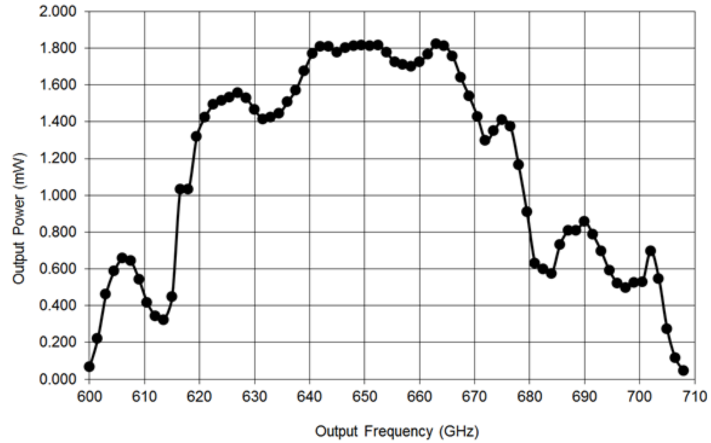






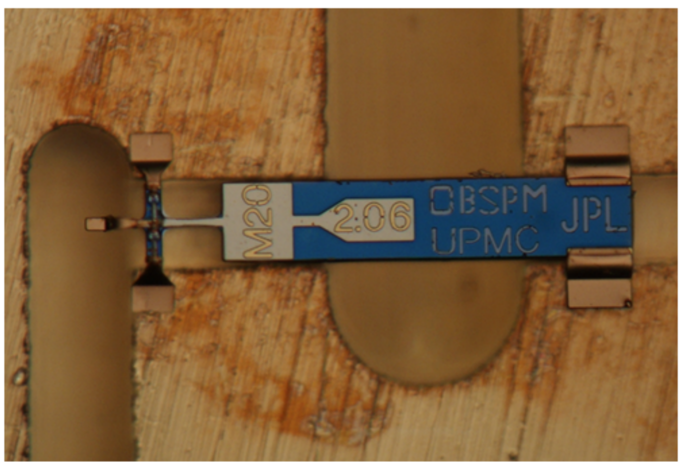
1.9 THz Multiplied Source

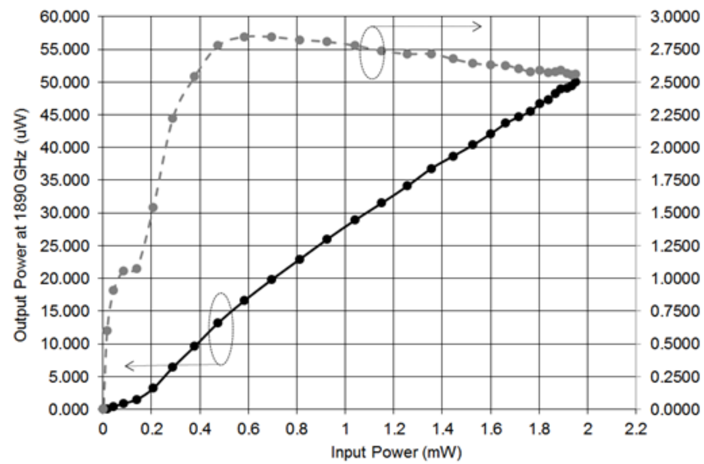




Second stage (X3)

- 2-anodes
- Membrane
- 1E17 cm^{-3} doping
- Pin=~40mW

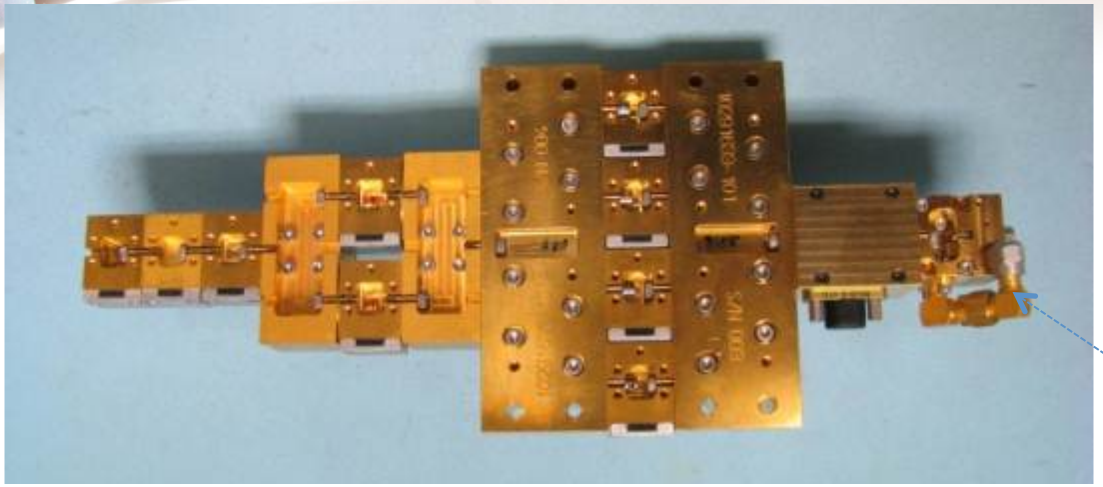




Third stage (X3)

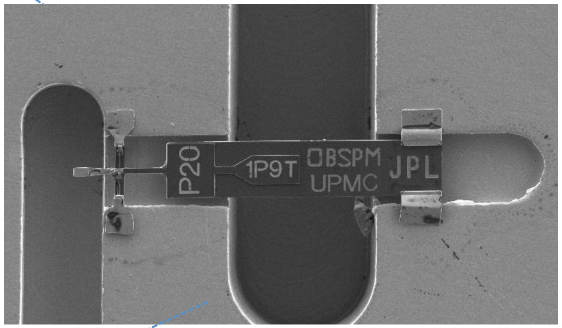
- 2-anodes
- Thin membrane
- 3E17 cm^{-3} doping
- Pin=1.5 mW

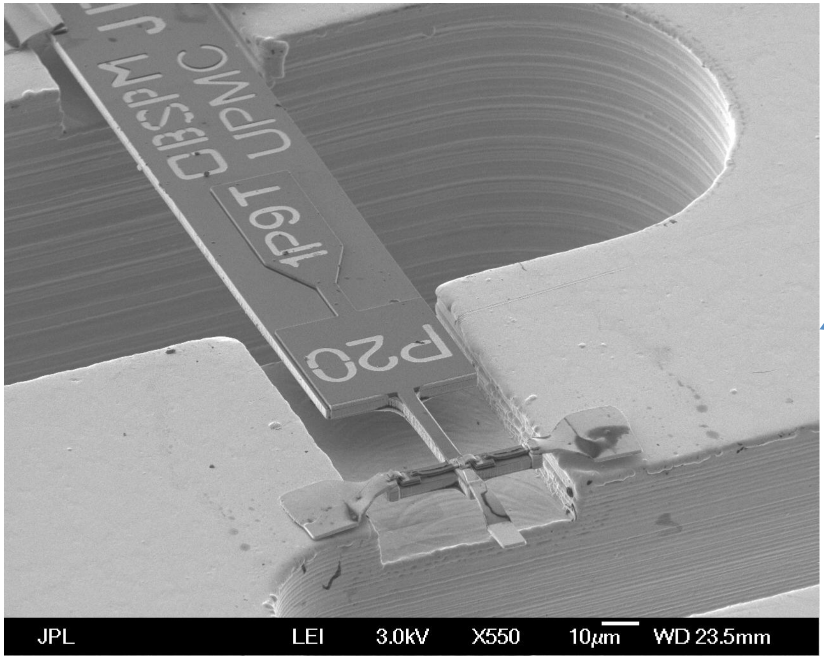
Single pixel 1.9 THz LO



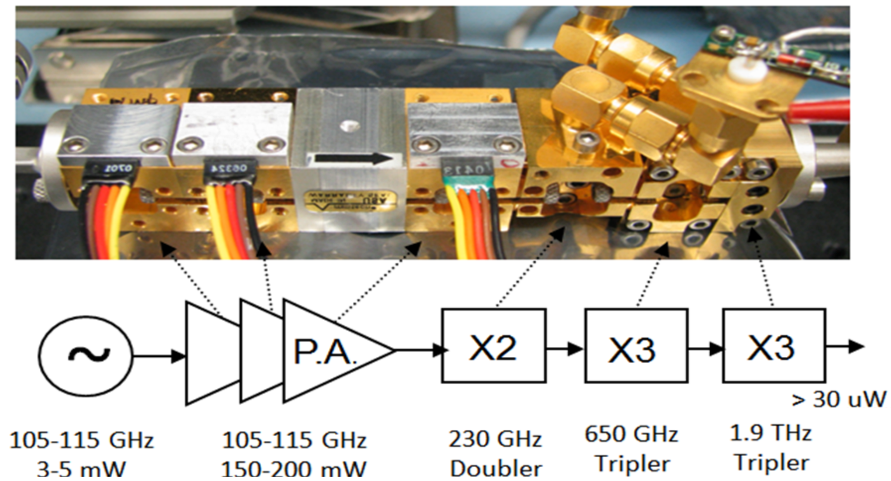
Used very successfully in Herschel HIFI

However, the 100 GHz power amplifiers are bulky and very expensive





NEXT GENERATION SINGLE PIXEL LO AT 1.9 THz

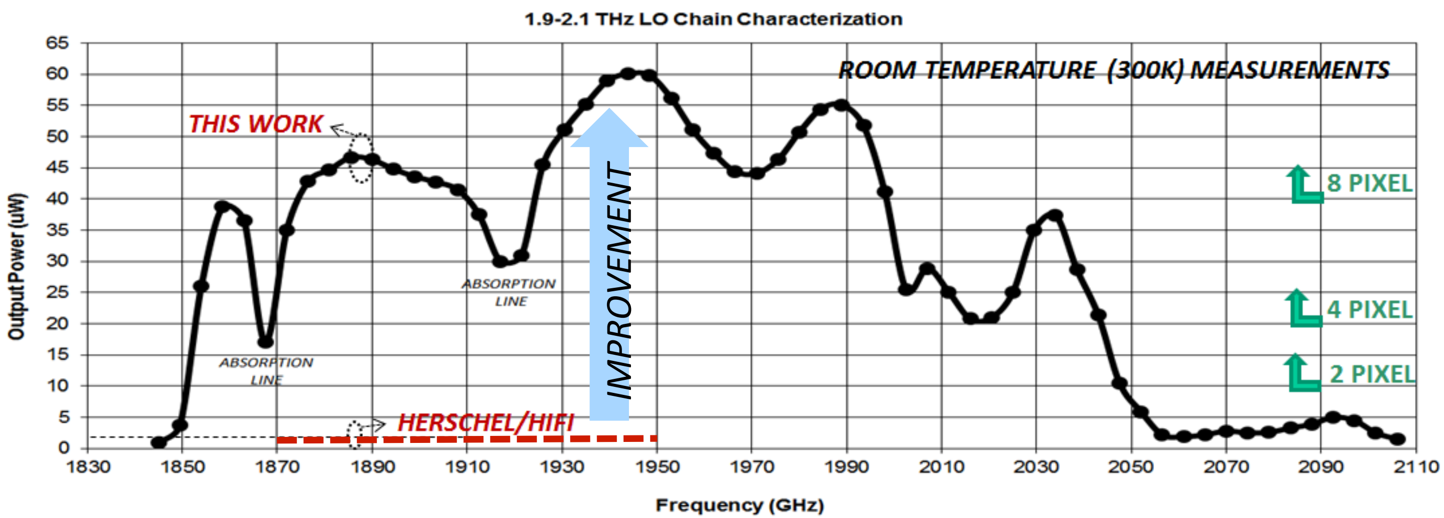


POWER BUDGET:

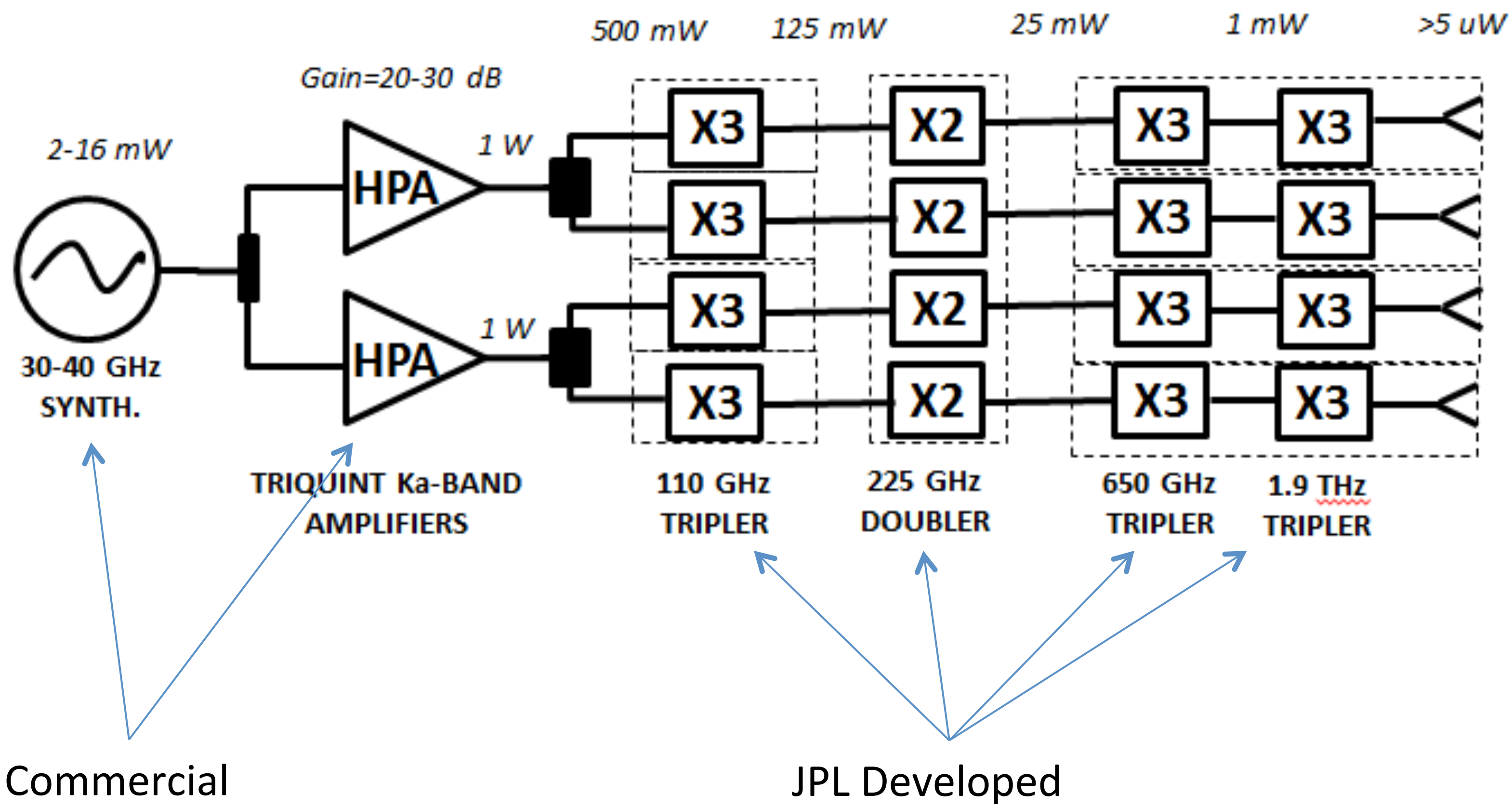
- **Power Amplifiers:** 5-6 Watt
- **First Stage Doubler:** 0.050 Watt
- **Second Stage Tripler:** 0.006 Watt
- **Third Stage Tripler:** ~ 0 Watt

- ***> x25 IMPROVEMENT OVER HERSCHEL (THIS WORK)***
- ***ENABLES MULTI-PIXEL OPERATION***

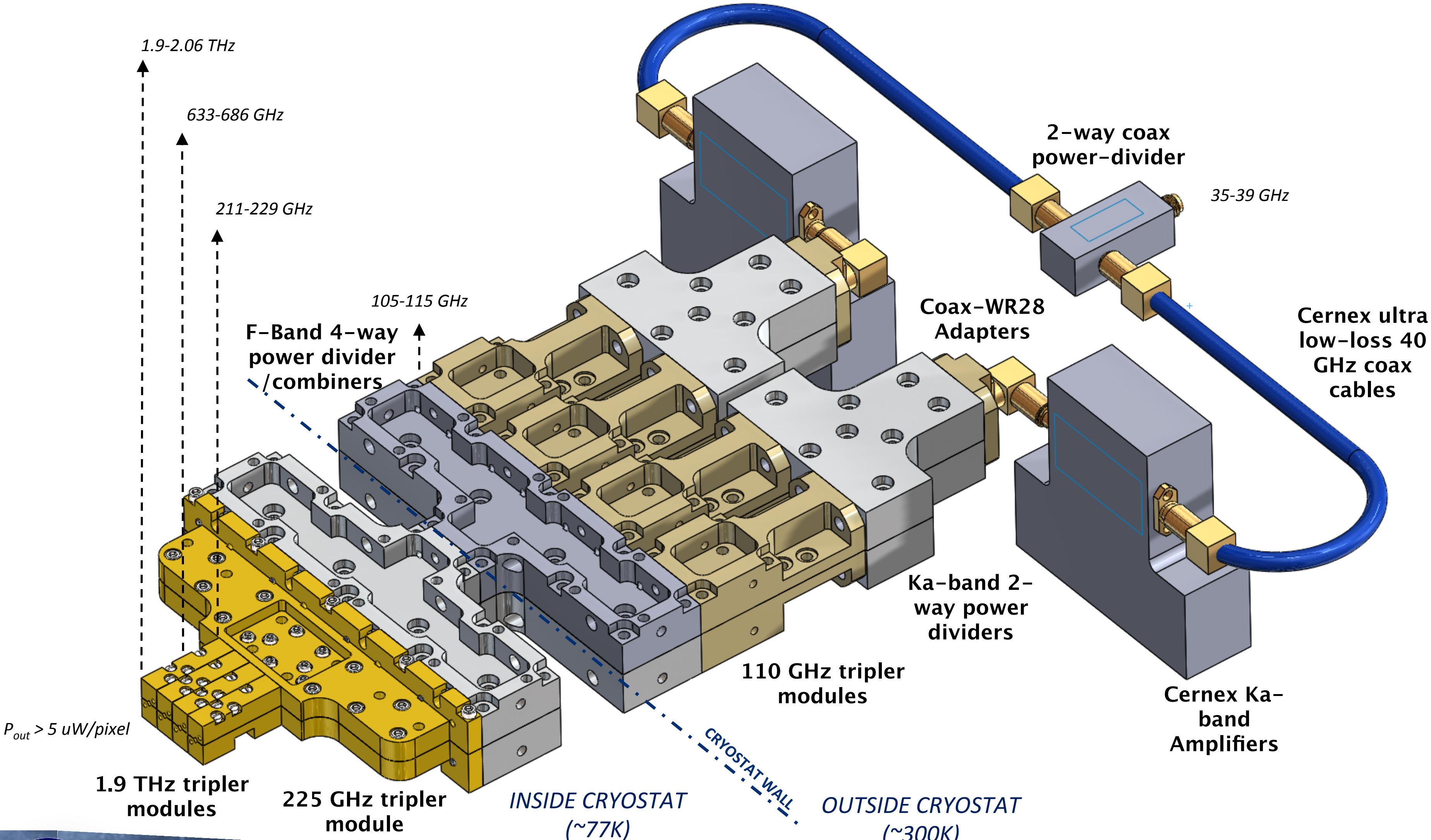
  (5 µW/pixel typical need for HEB based receivers)



MODIFIED SCHEME FOR THE 4-PIXEL LO



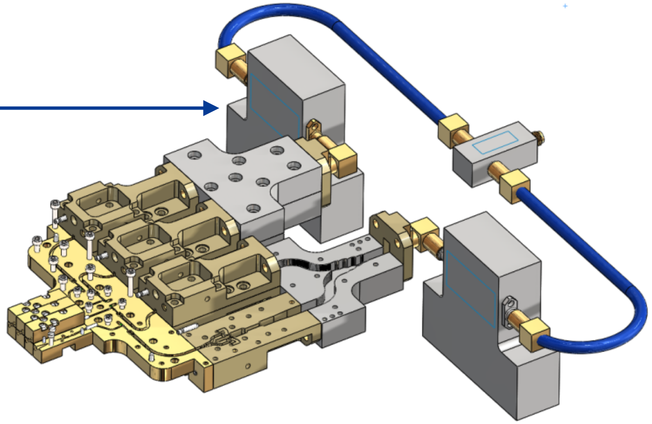
4-Pixel 1.9THz LO



4-PIXEL LO SUBSYSTEM MULTIPLICATION STAGES

Cernex Ka-band 1-W amplifier

Required gain >20 dB
Required bandwidth =33-40 GHz
Required P1sat=30 dBm
Fabrication completed: at Cernex (shipped to JPL)



Broadband Medium Power Amplifiers

FEATURES:

- Coverage From 0.5 to 65.0 GHz (Octave/Multioctave)
- Up to 2 Watt Output Power (@1dB Compression Point)
- Compact/Rugged Thin-Film Construction
- Economically Priced

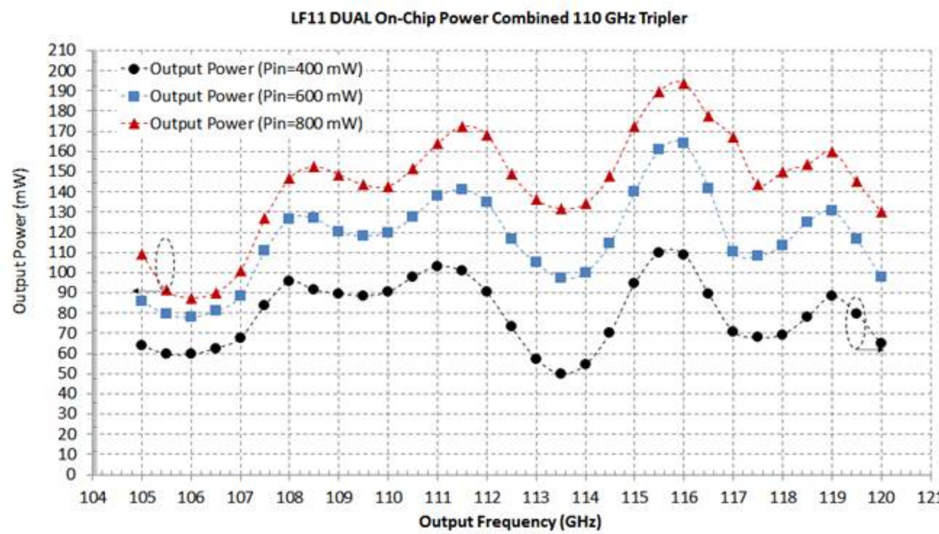
APPLICATIONS:

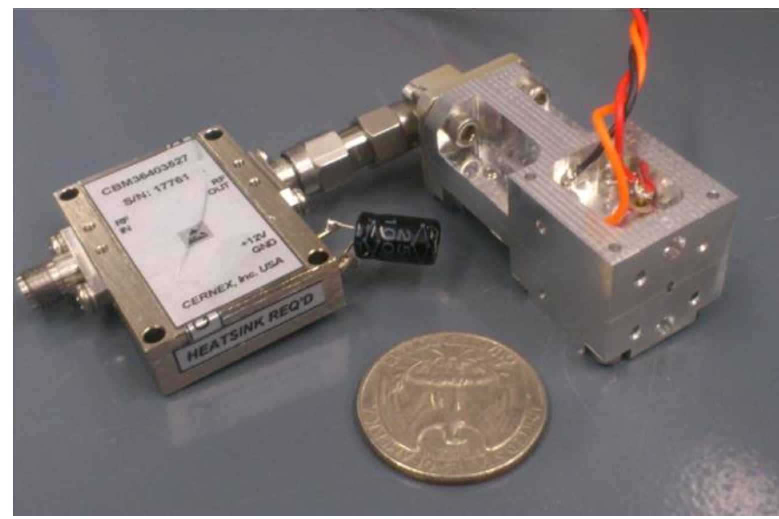
- General High Power Laboratory RF Sources.
- Output Amplifiers in test Equipment (ATE & AGE)
- Driver Amplifiers in RF Distribution Intermediate Power Amplifiers (IPA) in High Power Chaines.

CBM Series

NOVEL HIGH-POWER DUAL ON-CHIP POWER-COMBINED 110 GHz TRIPLER

- Avoids the use of F-band power amplifiers (not commercially available)
- Uses a Ka-band amplifier (very cheap) followed by a Schottky diode frequency tripler designed for high-power (~1 Watt) based on a proprietary novel topology invented at JPL
- Better thermal management (most of dissipated power at Ka-band)
- Record performance: 20-25% efficiency, 150-180 mW output per chip.

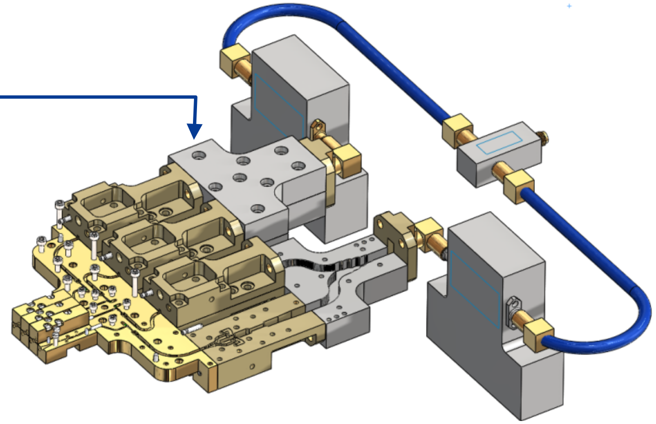


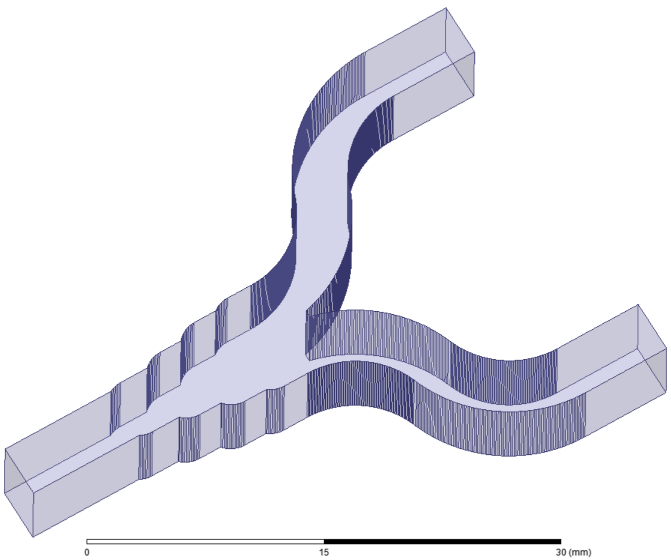


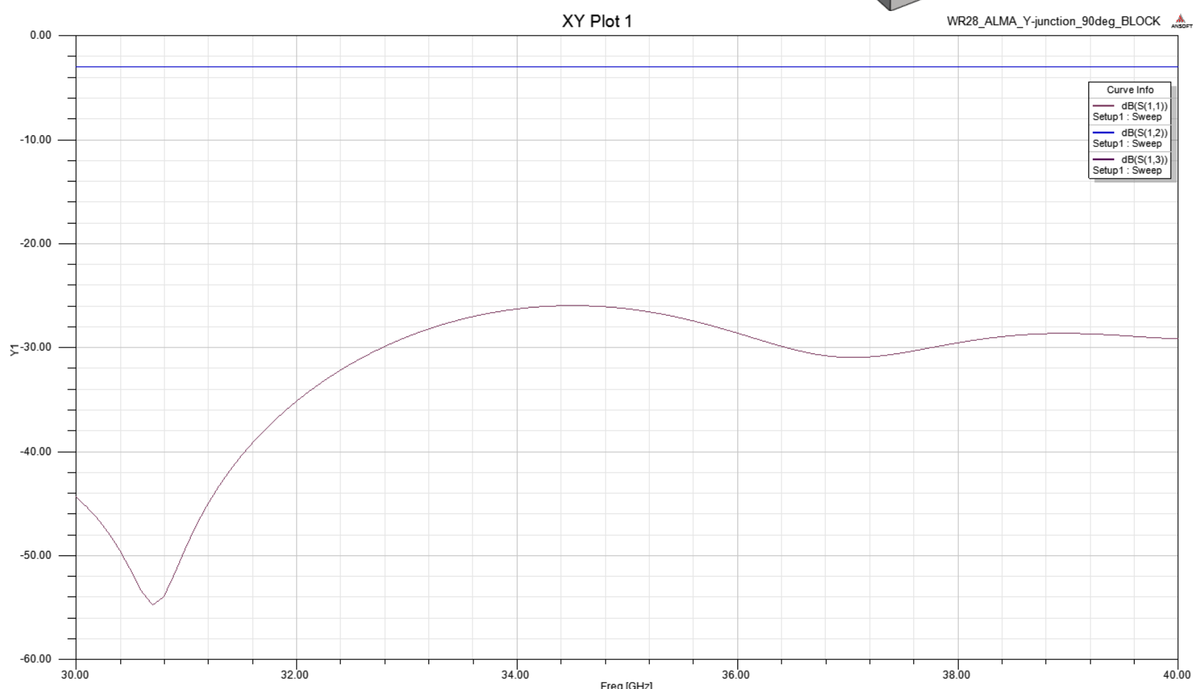
4-PIXEL LO SUBSYSTEM MULTIPLICATION STAGES

Ka-band 2-way power divider

Required S11 < -20 dB
Insertion loss =0.1 dB
Fabrication completed: FirstCut

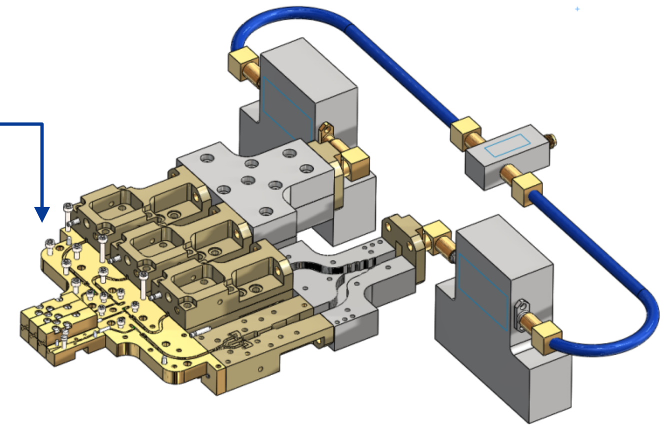


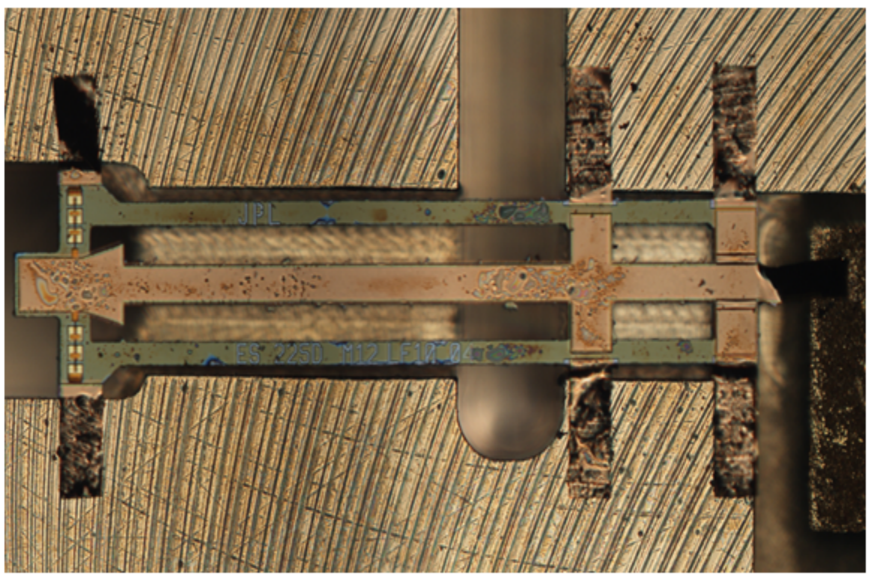


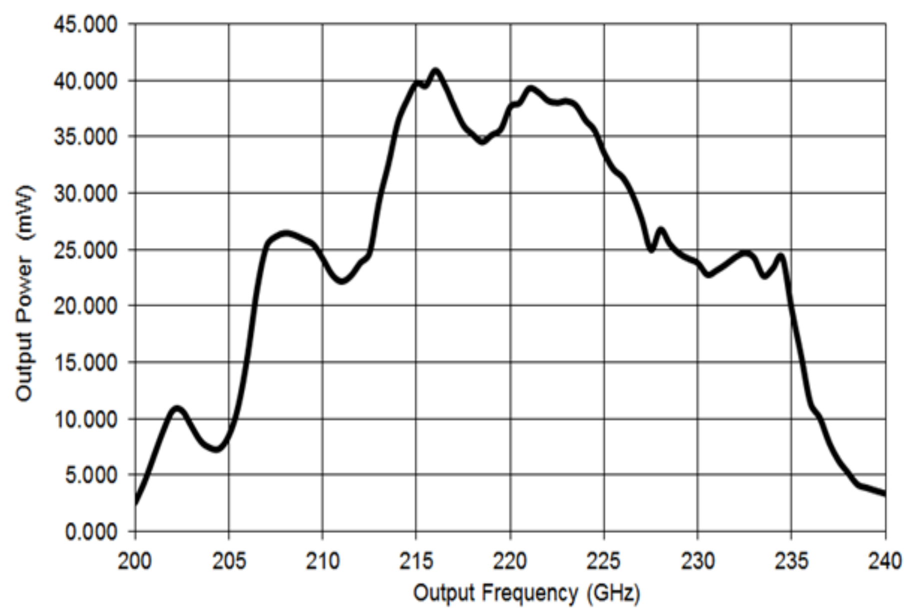


225 GHz doubler

Required output power/pixel > 20 mW
Required bandwidth: 210-229 GHz
Fabrication completed: LF10 fab run



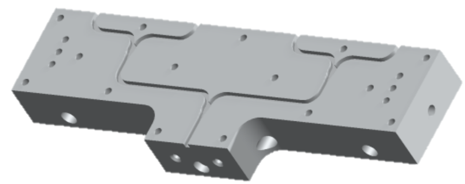


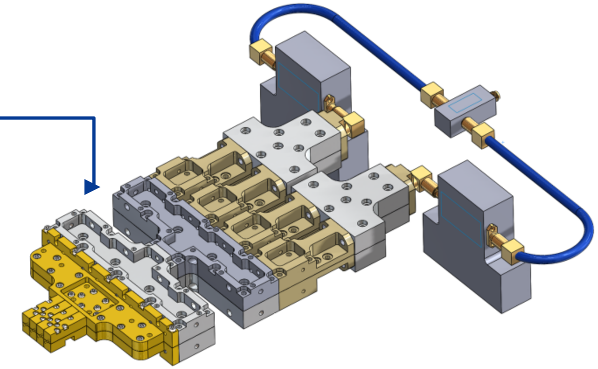


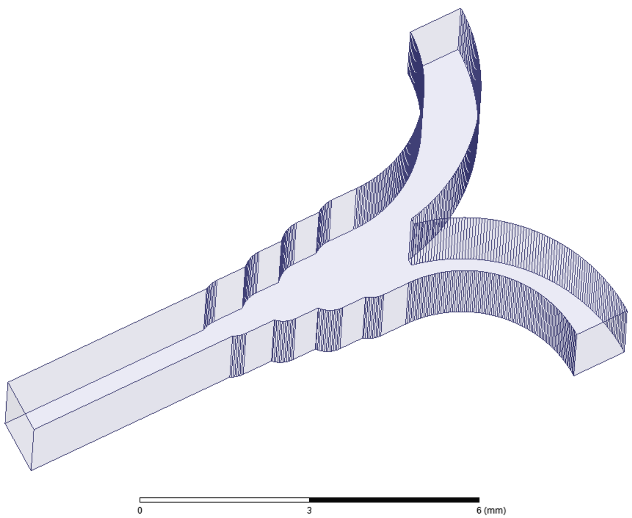
4-PIXEL LO SUBSYSTEM MULTIPLICATION STAGES

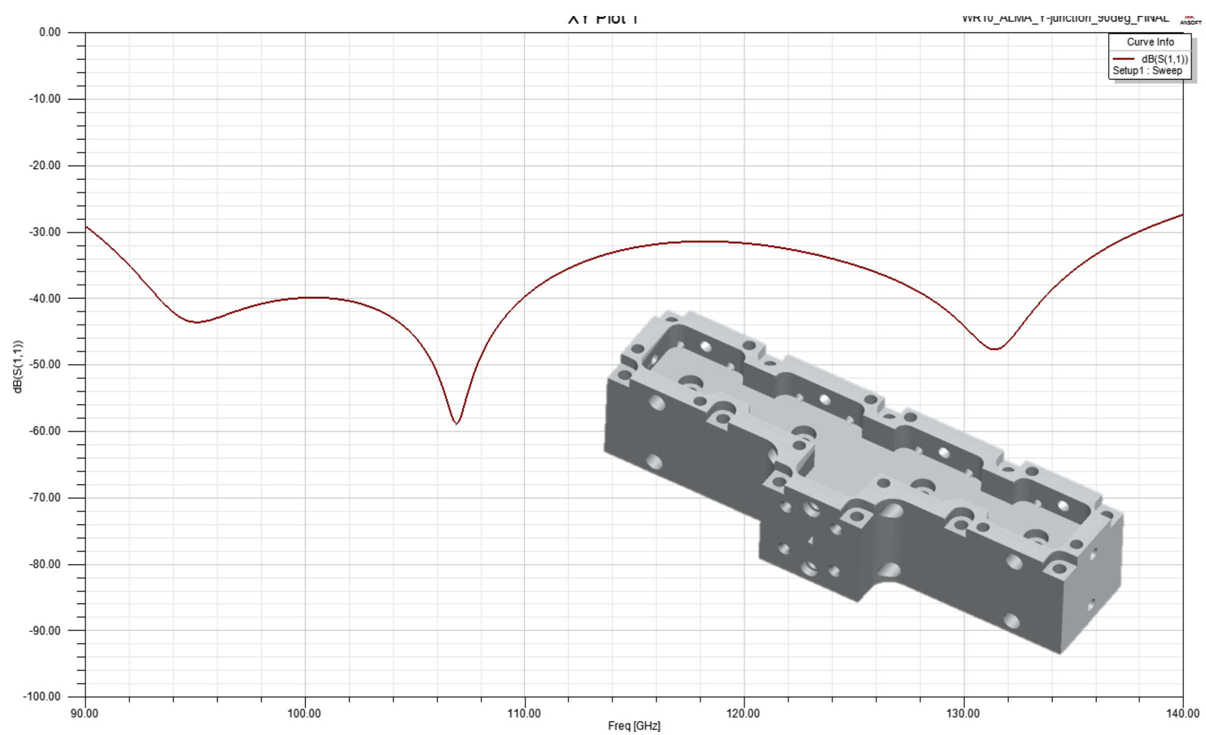
F-band 4-way power divider

Required S11 < -20 dB
Fabrication completed: FirstCut





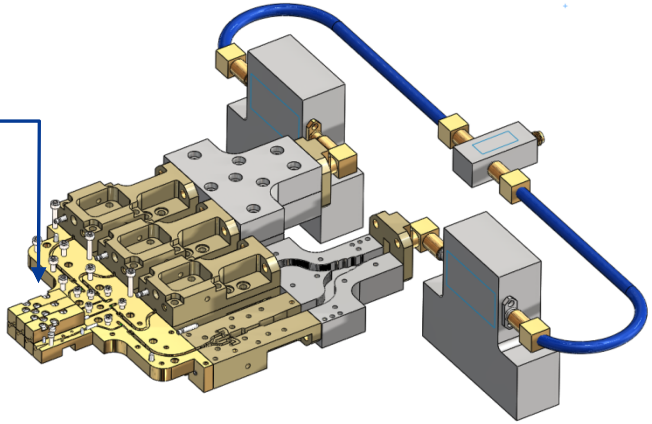


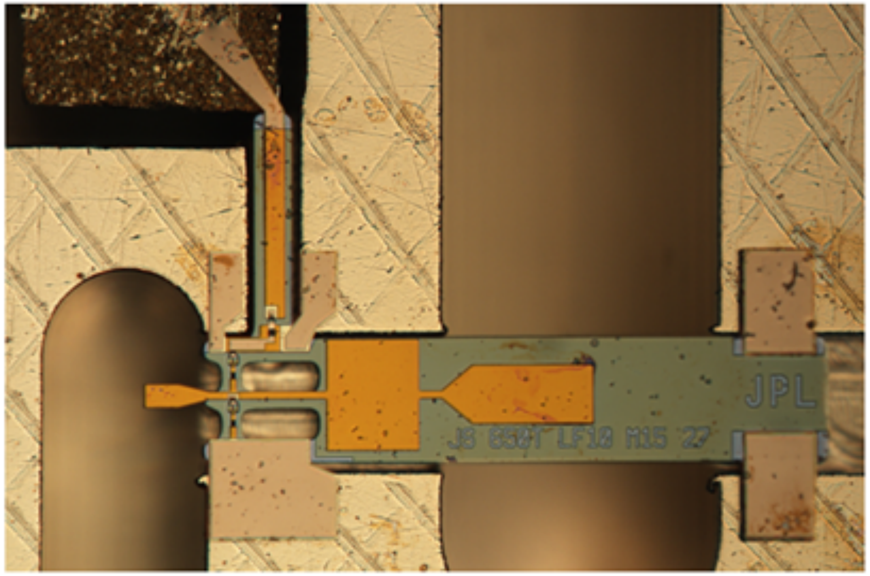


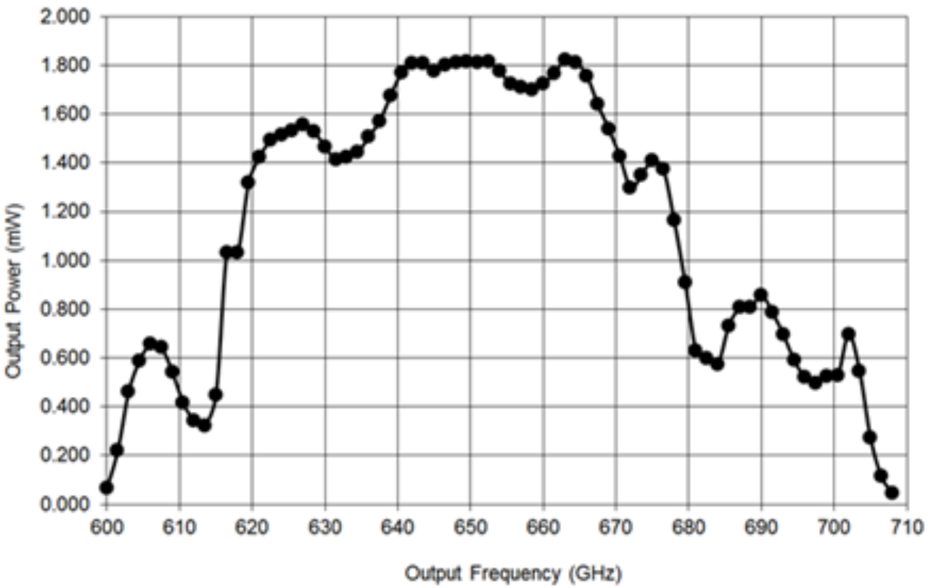
4-PIXEL LO SUBSYSTEM MULTIPLICATION STAGES

650 GHz tripler

Required output power/pixel > 0.8 mW
Required bandwidth: 633-686 GHz
Fabrication completed: LF10 fab run



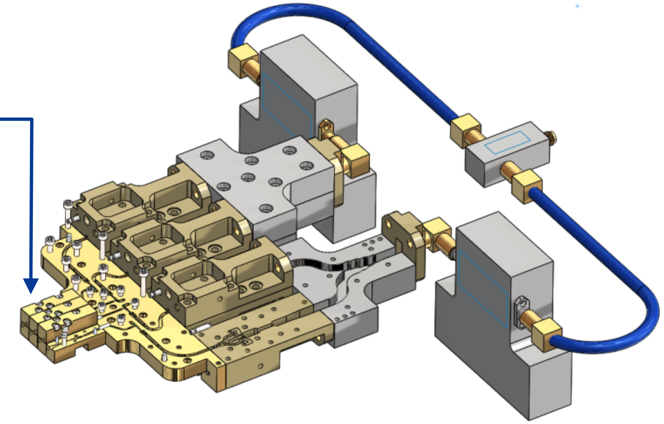


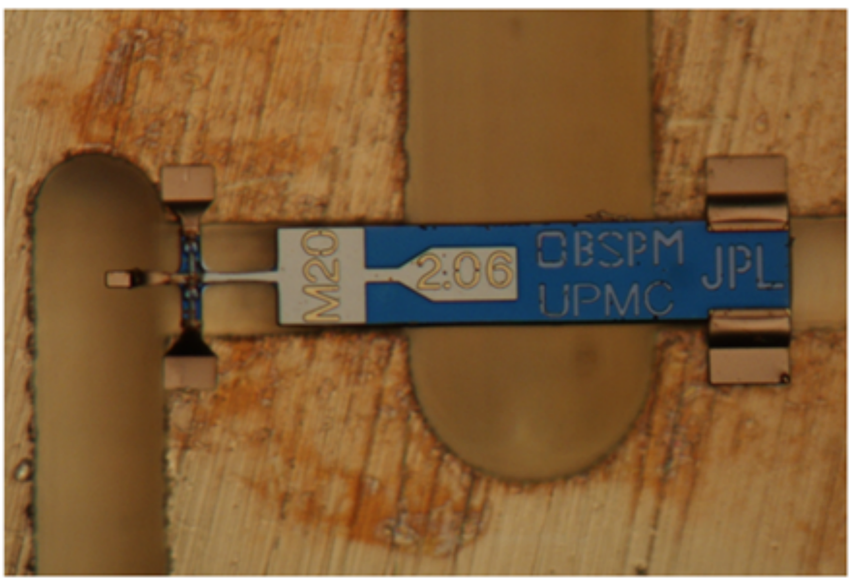


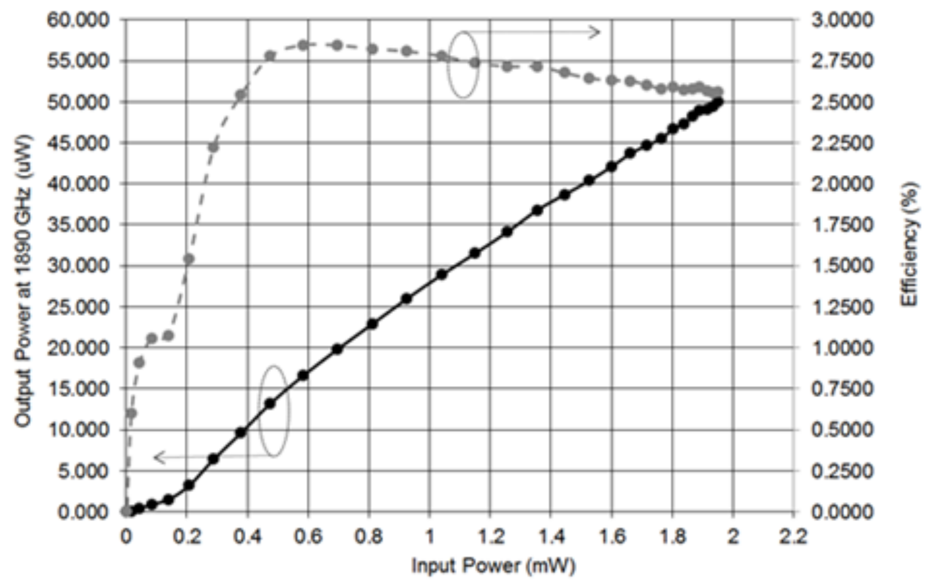
4-PIXEL LO SUBSYSTEM MULTIPLICATION STAGES

1.9-2.1 THz tripler

Required output power/pixel > 5 uW
Required bandwidth: 1900-2060 GHz
Fabrication completed: HF4 fab run





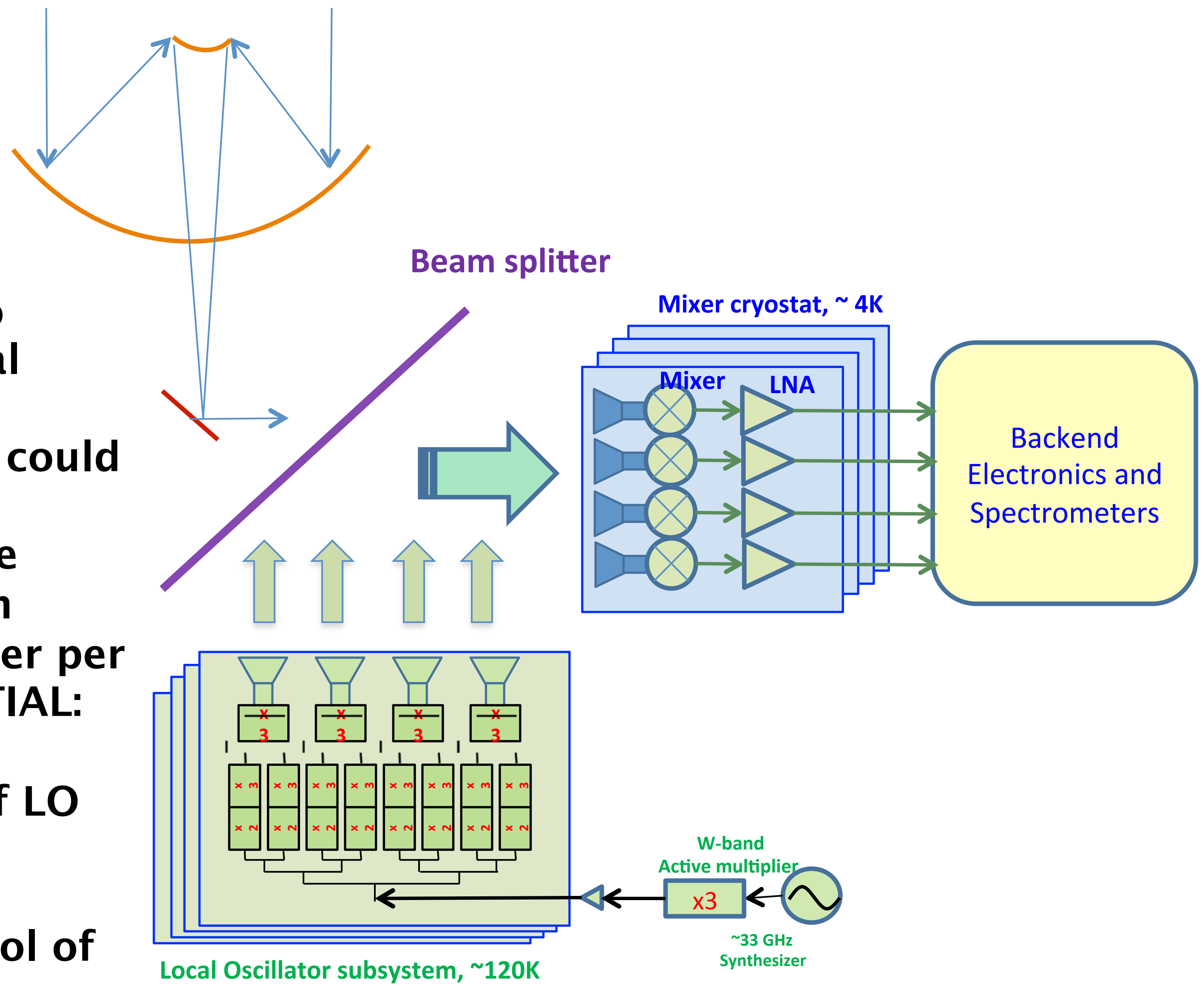


Development of robust array receivers

- ✓ QO coupling to provide thermal break
- ✓ Thermal break could be at the first multiplier stage
- ✓ Modular design
- ✓ Control of power per pixel IS ESSENTIAL:

Allows both

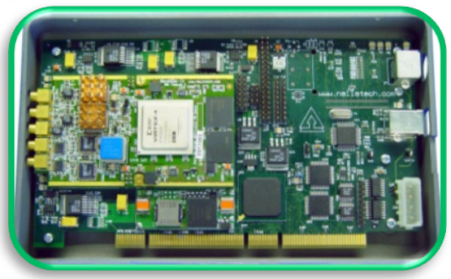
- optimization of LO power for each mixer and
- feedback control of LO power to ensure good baselines



The Second Major Technical Challenge- Spectroscopic Backends for Large-N Arrays

- Progress in digital technology has made multi-GHz bandwidth autocorrelators and FFT spectrometers possible
- Most systems have employed FPGA technology which is flexible, moderately expensive, and relatively bulky and power hungry
- A new paradigm is to use custom (ASIC) CMOS circuits which can offer greatly improved performance with dramatically lower power consumption
- The ability to piggyback on commercial development of CMOS technology is huge and this now applies to custom circuits in addition to FPGAs – the price barrier is rapidly disappearing

1st Generation CMOS Spectrometer



Current Generation FPGA – based Backend

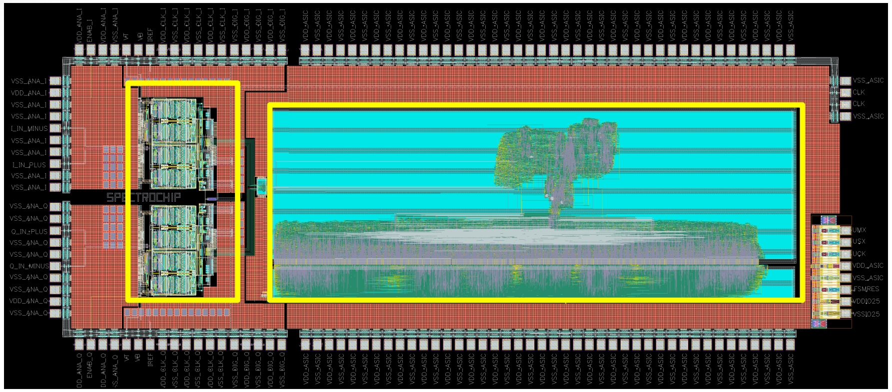
Performance Metric	Value
Power Usage	20-40 W
Weight	1-2 Kg
Volume	$100cm^3$
Channel Count	8192-16384
Sample Rate	8-10 GS/s
Unit Cost	$10000

First Generation CMOS Spectrometer 65nm Technology

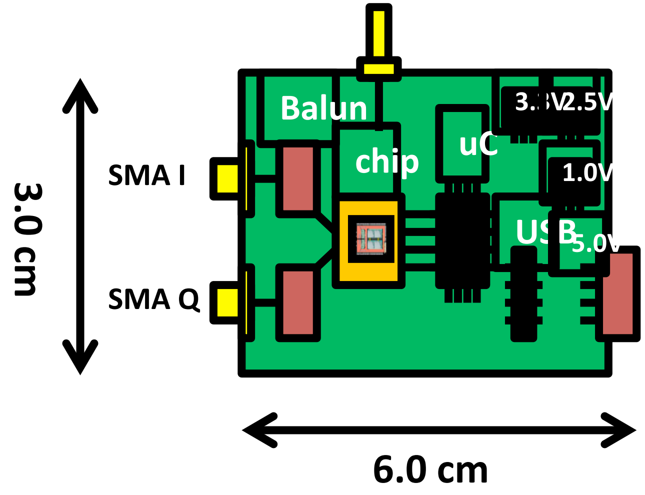
Performance Metric	Value
Power Usage	0.3 W
Weight	1-2 g
Volume	$1cm^3$
Channel Count	512
Sample Rate	2.2 GS/s
Unit Cost	$690 Prototype $0.50 Production

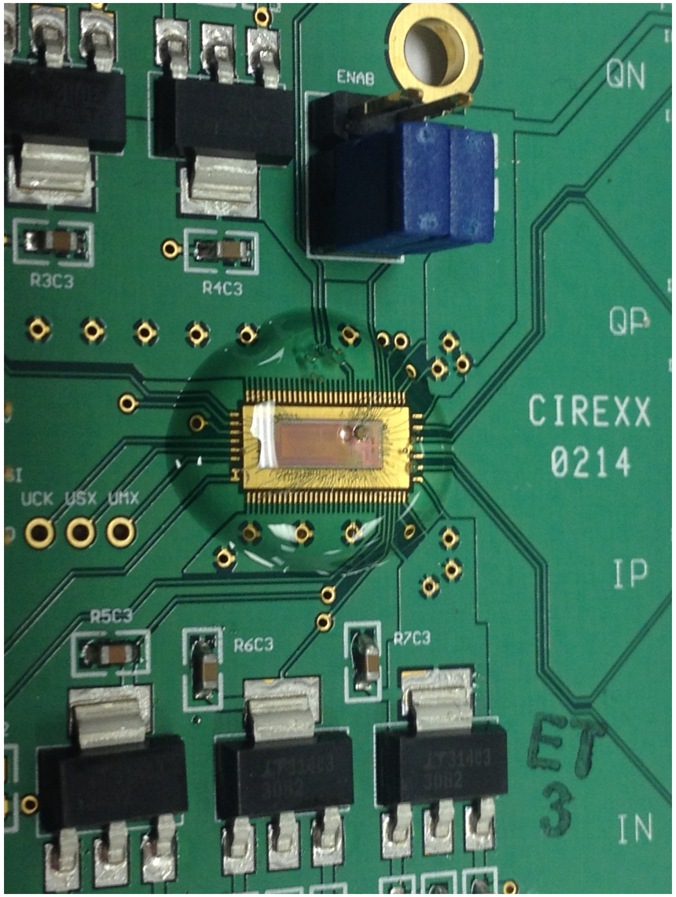
1st Generation CMOS Spectrometer

1.8 GS/s processor



7 bit ADC





Coming next: 28 nm technology 8 GHz BW; 8192 MHz

The Next Steps

- Assemble 4-pixel receiver system
- Test 1 GHz bandwidth "one-chip" digital FFT processor
- Fully characterize 4-pixel receiver system
- Verify 1.9 THz multi-flare angle feedhorn
- Test 8 GHz bandwidth 2038 channel CMOS spectral processor
- Implement 16 pixel system & test

Final Thoughts

- Short length HEB devices obtained from MSPU did not perform as expected after preliminary measurements. Additional work and better interface with MSPU is required. Due to lack of sufficient resources we did not pursue this further. However, we have been successful in getting funding for work with MgB2 devicies which shows considerable promise (PI is Boris Karasik).

- Single pixel LO source at 1.9 THz with more than 50 microwatts has been demonstrated. This is at room temperature and shows a ~x10 improvement over HIFI technology. Establishes a world record.

- A biasable tripler at 1.9 THz has been demonstrated. This validates the proposed approach of using the last stage tripler to provide optimum power for each mixer pixel.

- JPL designed and fabricated HEB devices have demonstrated SOA results up to 2.7 THz.